NOTE

This Microfiche meets the quality requirements of the American National Standard for Microfiche of Documents (ANSI PH5.9-1975). However, because of imperfections in the document from which it was made, it contains images that are illegible or difficult to read. The source document for this microfiche is the best copy that could be obtained prior to filming.

Congressional Information Service, Inc.
Washington, D.C.

CIS

Office of Technology Assessment

Congressional Board of the 98th Congress

MORRIS K. UDALL, *Arizona, Chairman*

TED STEVENS, *Alaska, Vice Chairman*

Senate

ORRIN G. HATCH
Utah

CHARLES McC. MATHIAS, JR.
Maryland

EDWARD M. KENNEDY
Massachusetts

ERNEST F. HOLLINGS
South Carolina

CLAIBORNE PELL
Rhode Island

House

GEORGE E. BROWN, JR.
California

JOHN D. DINGELL
Michigan

LARRY WINN, JR.
Kansas

CLARENCE E. MILLER
Ohio

COOPER EVANS
Iowa

JOHN H. GIBBONS
(Nonvoting)

Advisory Council

CHARLES N. KIMBALL, *Chairman*
Midwest Research Institute

EARL BEISTLINE
University of Alaska

CHARLES A. BOWSHER
General Accounting Office

CLAIRE T. DEDRICK
California Land Commission

JAMES C. FLETCHER
University of Pittsburgh

S. DAVID FREEMAN
Tennessee Valley Authority

GILBERT GUDE
Congressional Research Service

CARL N. HODGES
University of Arizona

RACHEL McCULLOCH
University of Wisconsin

WILLIAM J. PERRY
Hambrecht & Quist

DAVID S. POTTER
General Motors Corp.

LEWIS THOMAS
*Memorial Sloan-Kettering
Cancer Center*

Director

JOHN H. GIBBONS

This is an OTA Working Paper that has neither been reviewed nor approved by the Technology Assessment Board

J952-58

TECHNOLOGY AND HANDICAPPED PEOPLE

Working Paper #5

The Technology of Artificial Joint Implantation With Special Emphasis on the Hip and Knee

August 1983

CONGRESS OF THE UNITED STATES
Office of Technology Assessment
Washington, D. C. 20510

Preface

This volume contains papers written for OTA to assist in preparation of the report *Technology and Handicapped People.* OTA does not endorse these papers. In several instances, the OTA report reaches somewhat different conclusions because of additional information which was obtained later. These papers, however, may prove valuable for readers needing more detailed or specific information than could be accommodated in the final assessment report, and are being made available for such purposes.

THE TECHNOLOGY OF ARTIFICIAL JOINT IMPLANTATION WITH SPECIAL EMPHASIS ON THE HIP AND KNEE

Working Paper #5

Prepared for the Office of Technology Assessment
by

Dan Lawsen, M.D.

Long Island Jewish Hospital Medical Center
New York

Foreword

Technology exerts a powerful influence over the lives of everyone, making life easier, more fulfilling, but sometimes more painful and frustrating. This is especially true for people with disabilities. The appropriate application of technologies to diminishing the limitations and extending the capabilities of disabled and handicapped persons is one of the prime social and economic goals for public policy.

The Federal Government is deeply involved in programs that affect the development and use of technologies for disabilities. Congress and other institutions have been increasingly interested in how well programs that directly develop technologies and support their use have been performing. The Senate Committee on Labor and Human Resources requested the Office of Technology Assessment (OTA) to conduct a study of technologies for handicapped individuals. That study examined specific factors that affect the research and development, evaluation, diffusion and marketing, delivery, use, and financing of technologies directly related to disabled people. The problems and processes of the development and use of technologies were analyzed in the context of societal allocation of resources and the setting of goals for public policy. The main report of the study Technology and Handicapped People was released in May 1982.

This case is Working Paper #5 of the study. Working Paper #5 was authored by Dr. Dan Lawsen, now in training at the Long Island Jewish Hospital Medical Center, New York. A number of case studies will be published as part of the assessment and each will be issued separately. The case studies were commissioned by OTA both to provide information on specific technologies and to gain lessons that could be applied to the broader policy aspects of technology and disability.

Each author is responsible for the conclusions of specific case studies. These cases are not statements of official OTA position. OTA does not make recommendations or endorse particular technologies. These papers may prove valuable for readers needing more detailed or specific information than could be accommodated in the final assessment report and are being made available for such purposes.

ACKNOWLEDGEMENTS

This paper could not have been possible without the unfaltering help of numerous individuals, many of whom are cited in the reference section. However, special thanks must be given to Dr. David Banta who has been my guiding light since my arrival at Office of Technology Assessment in January 1981. The perspective given me by Dr. Jacqueline Perry was indispensible in helping me appreciate the length and depth of this complex technology.

The opportunity to work at Office of Technology Assessment and produce this work was initially provided through Professor Bess Dana of the Community Medicine Department of the Mount Sinai School of Medicine. Her support for my many endeavors over the past four years has been invaluable.

I wish to thank the entire staff of the Health Program at Office of Technology Assessment for their friendship, support, and enncouragement during my stay, especially Ginny Cwalina for all her invaluable assistance.

Finally, I am greatly indebted to the staff in the Department of Community Medicine at Mount Sinai for providing me with the necessary facilities to complete this project.

TABLE OF CONTENTS

Chapter Page

Acknowledgements
Glossary of Terms..

1. SUMMARY..1-1

2. INTRODUCTION.....................................2-1

3. THE CONTRIBUTIONS TO JOINT TECHNOLOGY AND THEIR MATERIALS...3-1
    Orthopaedic Surgeons..............................3-1
    Orthopaedic Bioengineers..........................3-2
    Manufacturers.....................................3-3
    Man-Made Materials Used in Joint Implants: Their History and Present Use.........................3-7

4. A HISTORICAL VIEW OF ARTIFICIAL JOINTS...........4-1
    The Hip...4-1
    The Knee..4-3

5. THE MODERN ERA OF JOINT IMPLANTATION: THE EVOLUTION OF THE ARTIFICIAL KNEE.............................5-1
    Artificial Knees: The First Generation...........5-1
    Artificial Knees: The Second Generation..........5-2
    Artificial Knees: The Third Generation...........5-5

6. THE MEDICAL INDICATIONS FOR TOTAL JOINT REPLACEMENT......6-1

7. COMPLICATIONS ASSOCIATED WITH JOINT IMPLANTATION..........7-1
    Infections..7-1
    Loosening...7-2
    Dislocation.......................................7-3

8. THE REHABILITATION OF JOINT RECIPENTS.............8-1

9. FACTORS CONTRIBUTING TO THE DIFFUSION OF JOINT IMPLANTS IN THE UNITED STATES.......................9-1

10. FEDERAL AGENCIES AND THEIR POLICIES TOWARD ARTIFICIAL JOINT REPLACEMENT TECHNOLOGY.......................10-1
    National Aeronautics and Space Administration (NASA)..10-1
    National Institutes of Health (NIH).................10-3
    National Institute of Handicapped Research (NIHR).....10-4
    Veterans Administration (VA)........................10-4
    Food and Drug Administration (FDA)..................10-6

11. SOME LEGAL CONSIDERATIONS OF JOINT IMPLANT TECHNOLOGY....11-1
    Implant Retrieval Analysis..........................11-1

12. ANALYSIS..12-1
    Patient Involvement.................................12-1
    Removing Obstacles to Progress......................12-2

13. APPENDIX: ANALYSIS OF THE ARTICLE: "AN ECONOMIC EVALUATION OF PREMARKET REGULATORY REQUIREMENTS," BY ELDON FRISCH

14. FOOTNOTES

15. REFERENCES

LIST OF TABLES

Table No.

1. Profile of Orthopaedic Manufacturers....................3-31
2. Results of Anametric Total Knee Arthroplasty in Patients with Osteoarthritis..........................5-9a
3. Results of Anametric Total Knee Arthroplasty in Patients with Rheumatoid Arthritis............................5-9a
4. Classification by Generic Terms........................10-8a of Artificial Hip and Knee Joints

LIST OF FIGURES

Figure No.

1. The Femur and the Pelvis................................2-1a
2. The Femur, Tibia, and Patella at the Knee Joint..........2-1b
3. The Range of Motion of the Knee.........................5-1a
4. The Gunston Knee Prosthesis.............................5-1b
5. The Geometric Knee Prosthesis...........................5-3a
6. The Patella Button......................................5-7a
7. The Anametric Knee Prosthesis...........................5-8a
5-8b

GLOSSARY OF TERMS

Actabular Cup: A man-made hip replacement component intended to replace the surface in the pelvis into which the head of the femur fits.

Acetabulum: The surface in the pelvic bone into which the head of the femur fits.

Arthrodesis: The fusing of a joint by surgical means.

Arthroplasty: An operation to restore joint function usually using man-made components.

Artifical Joint: Man-made component(s) implanted through a surgical procedure in order to eliminate pain and restore joint function.

Biocompartmental Joint Disease (of the Knee): Knee joint dysfunction, regardless of cause, which affects both femoral articulating surfaces of one knee and the matching tibial articulating surfaces.

Constraint: A property of artificial joints (such as shoulders and knees) which refers to the relative configurations of the articulating surfaces of the joint and their tendency to remain in contact under increasing stresses that could separate them. The more constraint present in an artificial joint, the more force that is needed to separate the components.

Cruciate Ligaments (of the Knee): The two crossing ligaments which are on the far-end of the femur and the near-end to the tibia and are "inside the joint." They participate in the network of ligaments stabilizing the knee. In many knee devices, these ligaments must be removed in order to properly implant the device over the femoral and tibial bony ends.

Cup Arthroplasty: A popular surgical procedure (in the 1940's - 1950's) whereby a metal "cup" was placed over the damaged femoral head to "mold" it back into the correct shape, thus reducing pain and restoring hip function.

Disclosure Agreement: A contract between several parties defining the confidentiality of discussions and negotiations of potentially proprietary information held by those parties.

Failure: Dysfunction of an implanted joint which occurs for any reason.

Femoral Condyle: The rounded far-end of the femur which comprises a portion of the knee joint.

Femoral head: The upper-end of the femur, the "ball" of the hip joint.

Femur: The thigh bone.

Fixation: The act of firmly attaching an artifical joint to the underlying bone.

Grout Agent: The load-bearing properties of a substance; used to describe the characteristics of "bone" cement.

Implantation: See arthroplasty.

Implant Retrieval Analysis: The applied science of studying implanted artificial joints removed from the body.

Intramedullary Stems: The elongated portion of the artificial joints that are cemented within the bone marrow.

Joint Capsule: The supporting ligaments tightly surrounding a joint.

Joint Fusion: See arthrodesis.

Joint Implant: See artificial joint.

Kinesiology: The science of movement, and the active and passive structures involved.

Loosening: The loss of attachment; referring to the bone, cement and device interfaces.

Patella: The knee-cap.

Polymethyl Methacrylate (PMMA): The cement used to attach devices to bone.

Prosthesis: See artificial joint.

Revision Surgery: Operations that re-make previously repaired joints which have stopped functioning properly.

Telemetry System: The science and technology of measuring quanties and transmitting the results over distances.

Tibia: The shin bone.

Tibial Plateau: The upper-end of the tibia, which comprises a portion of the knee joint.

Ultra-High Density Polyethylene UHD-polyethylene): A highly compact plastic polymer used extensively as a low-friction surface in artificial joint construction.

Unicopartmental Disease (of the Knee): Knee joint dysfunction due to any cause, which affects only one femoral articulating surface in one knee and its matching tibial surface.

Chapter 1
Summary

1. SUMMARY

This review of joint implantation technology* examines its history, aspects of the current state-of-the-art, and issues with regard to technology and its relationship to Federal policies. Artificial joints are intended to replace diseased human joints, thereby removing pain and restoring function. Approximately 10 percent of the U.S. population suffers from some form of arthritis, and 140,000 implantations of hip and knee joints were performed in 1976. Such devices are intended for patients with severe joint pains, unrelieved by traditional medical therapies. The most common diseases treated are osteoarthritis and rheumatoid arthritis. Patients with strenuous life styles, especially young patients, are not routinely offered the benefits of joint replacement.

The interest in this type of therapy originated with orthopaedists, and can be traced as far back as 1891. A progression of devices has appeared since the early 1900's, produced on an individual basis as a last effort to save patients from surgical procedures which eradicate the joint, but also provide permanent relief from pain. As man-made materials improved (such as stainless steels and Cobalt-Chromium alloys), device designs and the surgical procedures for their placement began to succeed. In 1961, the work of Sir John Charnley, using low-friction plastics and "bone" cement (polymethyl methacrylate, or PMMA) proved the breakthrough leading to the modern era of joint replacement.

Orthopaedists working in conjunction with bioengineers and the orthopaedic manufacturing industry, have continued to identify and propose solutions for diseases of human joints. They actively engage in evaluating joint technologies and many orthopaedists routinely offer this technology to eligible patients. Bioengineers have contributed to the understanding of the musculo-skeletal system and have provided a strong engineering backdrop for the development of new joint designs. The manufacturers have incorporated new techniques in metallurgy and materials, as well as the manufacturing techniques peculiar to implants, into the production of high-quality medical grade joint implants. They also provide custom-services to surgeons.

The research and development of the modern total artificial knee prosthesis is an example of the methods used by orthopaedists and bioengineers to evaluate new designs. Three generations of knee prosthesis have appeared over the past 15 years. The first generation is characterized by the four-part Gunston knee, the second by the geometric and duocondylar designs, and the third generation by the total condylar prosthesis, the anametric knee, and the multiple variations now available of those designs. Anecdotal clinical experience is the means of evaluating such knee systems.

---

*The joint implant technology information given in this paper is current to June, 1981.

As with any surgical procedure, complications can arise: loosening (by the far the most perplexing and troublesome cause of failure), infection, dislocation, and other systematic illnesses caused by the stresses of this surgery. Information about joint technology, procedures, research, and the spread of these devices travels by the traditional methods in medicine, depending heavily upon medical societies, continuing education courses, and physician training programs.

The Federal agencies involved in the basic research support of the human musclo-skeletal system include the National Institutes of Health and the Veterans Administration (VA). Advances in the scientific understanding of joint implant technology and designs has been funded by the National Institute of Handicapped Research, the National Aeronautics and Space Administration, and the VA. The 1976 Medical Devices Amendments to the Food, Drug and Cosmetics Laws gave the Food and Drug Administration (FDA) responsibility for implementing and enforcing these statutes.

There are few accurate estimates on the extent of diffusion of this technology. Patients are "passive" participants in the development of replacement joints, often agreeing to allow evaluations of their newly implanted devices. The lack of adequate joint implants for young vigorous patients has proven a formidable problem. As in other medical technologies, safety and effectiveness issues in joint technology are largely unsettled. There are numerous evaluation schemes for joint designs evident in the literature but the literature is particularly devoid of well-planned prospective clinical trials. Federal policies on safety and effectiveness are generally lacking. Doubts exist with regard to the ability and methods used by the FDA to administer the 1976 Amendments.

The orthopaedic community is aware that gaps exist in their knowledge and understanding of joint implant technology which need to be addressed in future research endeavors conducted by trained clinicians and bioengineers. Poor Federal interagency coordination has made research funds difficult to obtain on occasion. The perceived lack of coordination, cohesiveness, and direction on the part of the FDA in promulgating regulations, guidelines, and policies has been a factor in slowing innovation. Manufacturers have been reticient to undertake expensive clinical trials without guarantees from the FDA that the collected data will remain acceptable years after the beginning of such trials. The Custom Device Provisions of the Amendments has proven to be valuable to manufacturers for "pre-testing" potentially useful new devices, without encountering the regulatory requirements of the Medical Devices Act. However, there has been a growing tendency for manufacturers to move their research and development of new materials and new devices outside the United States, in order to avoid the Amendments entirely.

Chapter 2
Introduction

2. INTRODUCTION

The desire to replace worn parts of the body is easily understandable. Various devices have been created to meet the needs of people whose bodies have worn out: artificial heart valves, silastic blood vessels, artificial kidneys, and even false teeth. Joint replacement or joint implantation refers to surgical procedures which replace the natural joint with one man-made. There are several ways to bring this about: replace one surface of the joint leaving the other intact or alter all surfaces of the joint and fit with replacement parts. The latter technique is referred to as Total Joint Replacement, or Arthroplasty. Within the context of this work, reference to joint replacement or joint implantation will always conotate replacement of the total joint.

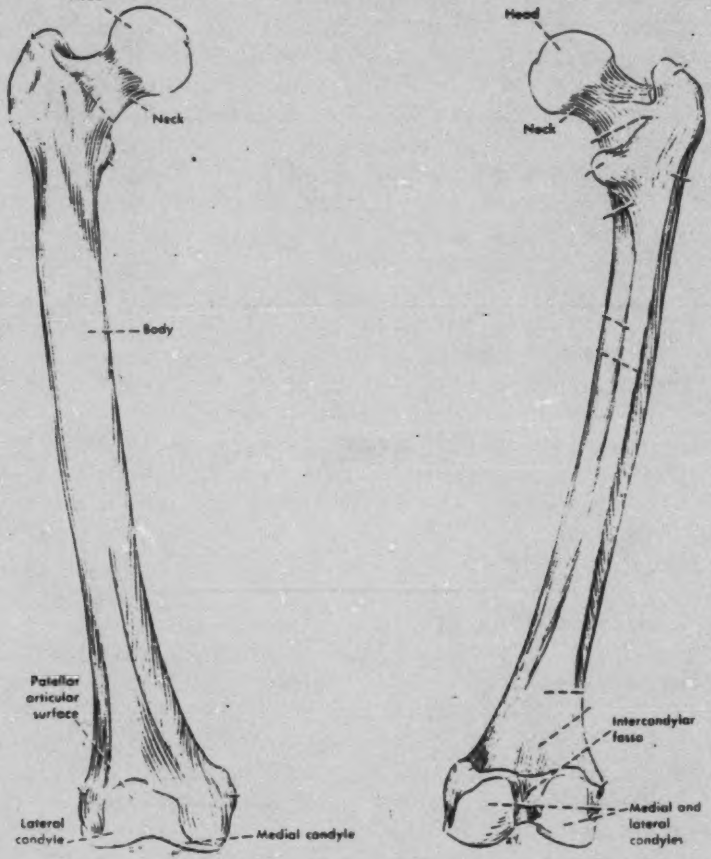
Many joints of the body are potentially replaceable, but only replacement of the hip and knee joints are common. The hip joint (fig. 1) is essentially a 'ball and socket' bearing-surface. The head of the femur (the ball) is in contact with the acetabular cup of the pelvis (the socket). On the joint surface a complex interaction takes place between bone lined with cartilage and fluid that circulates within--providing a very low friction surface for movement. Stability of the hip joint is achieved through a capsule composed of tough tissue and ligaments and the various muscles of the pelvis, buttocks, and upper thigh surrounding the joint.

The knee is the most complex of human joints. A common analogy is drawn to the hinge mechanism, but this does not reflect the varied motions found at the knee. As diagrammed (see fig. 2), the femoral condyles and tibial plateau slide along a pair of cartilage pieces (menisci) interposed between the two bones. Another sliding surface exists between the femur and the patella which has the quadriceps muscles attached to it. As the kneee flexes, the patella slides along the femur underneath. Stability about the knee is more precaurious than around the hip because there is less musculature to stabilize the knee. Therefore, the knee is highly dependent on the menisci, the integrity of the surrounding ligaments, and the joint capsule for support. There are ligaments not only around the knee joint, but inside the joint space as well (cruciates), to help maintain proper stability and alignment between femur, tibia, and patella.

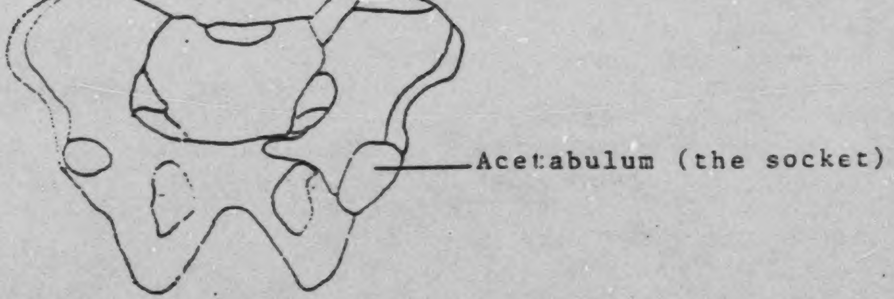
Diseases of the bone, cartilage, muscle, or ligaments can deform and/or destroy joints. Often diseases in one area tend to secondarily damage other facets of the joint's structure over time, altering the entire geometry and physiology of the joint. The most common diseases of the joint cause inflammation at the joint's surfaces, and are collectively referred to as arthritis. If arthritis is severely handicapping, then a joint replacement may be offered to relieve the pain and restore motion to that limb. Osteoarthritis and Rheumatoid Arthritis are the most common forms of arthritis. In the 45 to 64 year-old age category 1,254,000 people were estimated to have severe arthritis in 1970; 1,691,000 people aged 65 years and over are thought to have severe arthritis as well (44).

The 1969 U.S. Health Survey reported that over 10 percent of the U.S. population had arthritis or gout severe enough to require sufferers to seek medical attention.

Figure 1
The Femur and the Pelvis

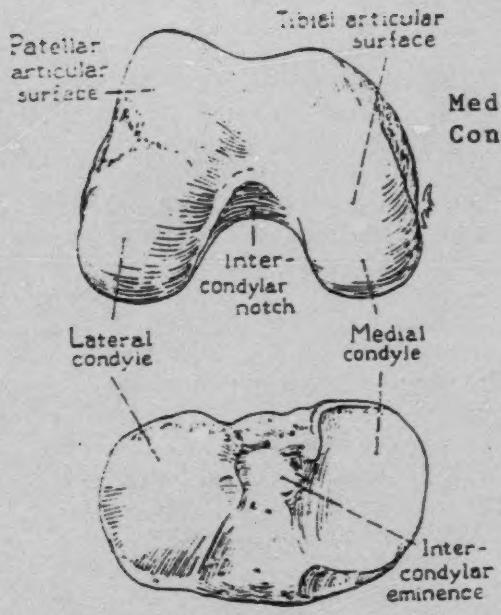

Head
Neck
Body
Patellar articular surface
Lateral condyle
Medial condyle
Head
Neck
Intercondylar fossa
Medial and lateral condyles

anterior view posterior view

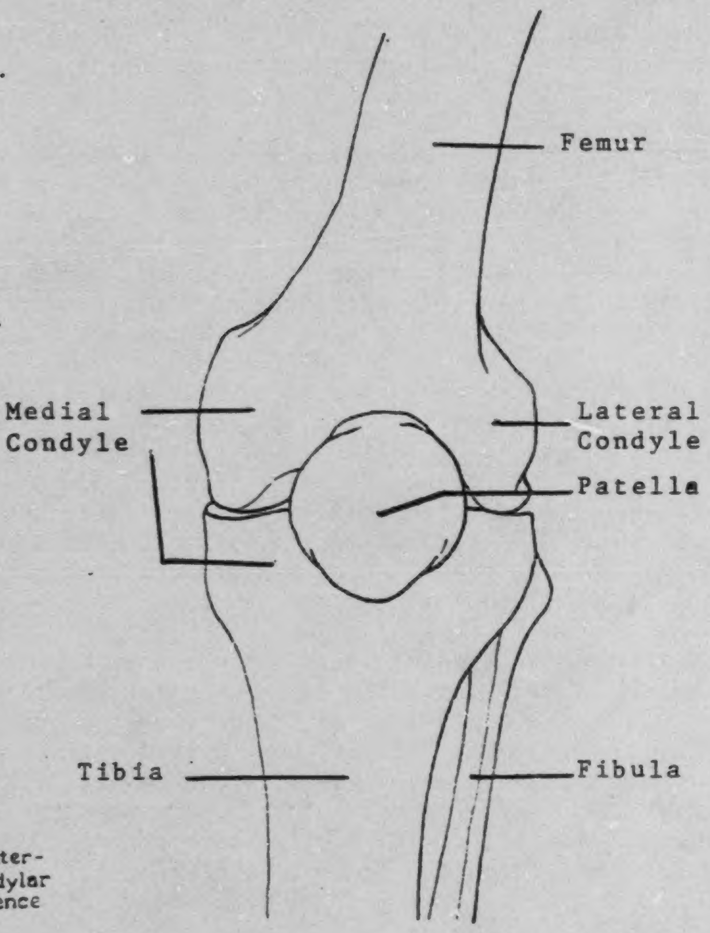

Acetabulum (the socket)

Reprinted with permission from: Hollenshead, W.H., Functional Anatomy of the Limbs and Back, 5th edition, W.B. Saunders, Philadelphia, Pennsylvania, 1981, p. 237.

Figure 2
The Femur, Tibia, and Patella at the Knee Joint


Patellar articular surface
Tibial articular surface
Inter-condylar notch
Lateral condyle
Medial condyle
Inter-condylar eminence

Articular surfaces of the femur and tibia


Femur
Medial Condyle
Lateral Condyle
Patella
Tibia
Fibula

The figure on the left was reprinted with permission from: Classon, D.K. and Rosse, Introduction to the Musculo-Skeletal System, Harper & Row, Philadelphia, Pennsylvania, 1970.

In 1973, the Social Security Administration reported paid disability benefits for osteoarthritis to 4.9 percent of claimants aged 50 to 54. This figure rose to over 9.2 percent of claimants over 60 years old. In all age groups over the age of 50, osteoarthritis was the second most frequent cause for disability payment by Social Security (44).

In all, 13 million persons have some form of osteoarthritis and 5 million persons suffer with Rheumatoid Arthritis. Osteoarthritis in the hip afflicts 8.4 percent of those men, and 3.1 percent of those women. Osteoarthritis of the knee affects 11.1 percent of the men, and 15.1 percent of the women. Therefore, over 4.9 million men and women have either osteoarthritis of the hip and/or knee.

The cost of all types of arthritis to the nation was estimated in 1975 to be over $13 billion. Physicians were paid $860 million for their services, and hospitals received over $1.5 billion. Another $4 billion were estimated to have been lost in productivity. The remainder has been attributed to related diseases and intangible losses suffered by the patients and their families (44). Many of the people so afflicted are potential candidates for joint replacements of some kind, not necessarily of the hip or knees.

Unfortunately, estimates on the numbers of joints replaced in the U.S. are sparse and of questionable accuracy. One estimation was made in an article published in 1978 (39). Statistics were collected from sources including: the Veterans Administration, the Orthopaedic Manufaturers, the Medicare system, and the Commission on Professional and Hospital Activities for 1972. The article estimates that 55,000 total hip replacements had been performed, and only 4,000 knee replacement. By 1976, however, over 80,000 hips were done, and 40,000 knees (39).

Because joint implantation has achieved wide acceptance in the United States, it is well suited to serve as a representative example of a medical device. This report describes the different groups which contribute to the research, development, diffusion, and evaluation of joint implants. It provides a historical overview of these devices and traces their introduction into the U.S. As an example of ongoing technology research, development, and evaluation, the artificial knee replacement will be examined in great detail. The role of the Federal Government is described as it relates to the different stages of this medical technology. Finally, the interactions occurring between the participating groups, and the issues which arise, will be highlighted and discussed separately in Chapter 12.

Chapter 3

The Contributions to Joint Technology And Their Materials

3. THE CONTRIBUTORS TO JOINT IMPLANT TECHNOLOGY AND THEIR MATERIALS

This section identifies and describes the numerous participants in joint implantation technology. Included among them are: orthopaedic surgeons, bioengineers, implant manufacturers, and the recipients of these devices. In order to familiarize readers with the man-made materials which make joint implantation possible, a section on materials currently in use, and some historical notes on them has also been provided.

Orthopaedic Surgeons

Orthopaedics is a medical specialty primarily interested in the diseases afflicting the musculo-skeletal system. Orthopaedists complete four years of medical school, as well as a specialty training program spanning approximately five years. As in other medical-surgical specialties, orthopaedists can become board certified if they take and pass exams given by the American Board of Orthopaedic Surgeons. In 1978, there were approximately 12,350 orthopaedists in the U.S. (32a). Today, orthopaedic residents are routinely trained to evaluate patients for artificial joints and to perform the surgical operations. However, this technology is only 15 years old and thus requires that many practicing surgeons must learn about these implants long after the completion of their formal training (84).

Usually, orthopaedists are asked to treat patients when medical measures are no longer helpful. Therefore, surgeons are typically exposed to the physiologic, anatomic, and functional abnormalities manifested by severely diseased joints. In the past, such patients were treated by surgeons with methods that were crude but satisfactory in ending the pain of those diseases. The traditional treatment (of last resort) has always been arthrodesis, or joint fusion. This consists of joining the bony ends of the joint and allowing it to heal into a solid bone, effectively eradicating the joint. Pain is always relieved, but motion about that joint is permanently ended. Fusion of the knee joint eliminates motion of the lower leg in relation to the thigh. The extra energy required to move about with this 'peg leg' may be over 20 percent of normal (69). Patients already weak might be prevented from ever walking again because of the extra energy requirements. Dissatisfaction with outcomes such as these has been the impetus for orthopaedists to seek better ways to treat joint pain and immobility.

Early artificial joints resulted from the designs of orthopaedists manufactured by private companies in very small quantities. They were placed in only the few patients who put little stress on the devices. As joint technology expanded and improved, many more orthopaedists became involved in their design and use. With the help of orthopaedic bioengineers and/or manufacturing engineers, joint design alternatives are evaluated and tested, and sometimes incorporated into devices. If a device is successful, the orthopaedists get the satisfaction of providing a solution to a joint disease, often receiving recognition for their contributions. However, with much of the early pioneering work in joint implantation completed, some orthopaedists have become interested in evaluating artificial joints after they have been implanted. In the past, the device's inventor also evaluated the implant. In the coming years, orthopaedists not associated with the design of a device will probably participate in such evaluations as a result of the Medical Devices Amendments of 1976 which are described in detail in Chapter 10.

While most orthopaedists are not engaged in implant development or evaluation, many do offer these devices to their patients. Surgeons must select the device they feel is the best for their patients. Often the consideration in making those decisions is based on multiple factors. The surgeons must base these decisions on the experience and knowledge they have accumulated over their years of training and practice. Such information may be gathered from the medical literature, meetings and conferences, as well as workshops and courses. Other considerations are: careful evaluation of the surgeon's own skills and the complexities of implanting particular models of joint implants. In the final analysis, like any other field in medicine, the orthopaedist's judgment of many interacting factors results in a particular level of care for patients.

In considering the information presented in this report, it is important to remember that the driving force in joint implant technology has been orthopaedists. They provide the insight and understanding of joint pain and dysfunction, as well as the goals of therapy, which to a large extent dictates the activities of bioengineers and manufacturers. Usually, patients do not participate in the decisionmaking processes, but are often asked to participate in studies on the joints once implanted.

Orthopaedic Bioengineers

The early designs for joint replacements did not adequatedly consider the basic engineering principles governing their function in humans(9,27,69,77). The technological boom that swept across medicine in the 1950's orthopaedics. To many, the founder of modern orthopaedic bioengineering or biomechanics was Carl Hirsch, a Swedish engineer. American orthopaedists such as Charles Bechtol, George Gallante, Victor Frankel, and Ernest Burgess began to appreciate the need to apply sound engineering principles to the mechanical problems posed by joint replacement (26,50).

Presently, biomechanics is taught on the graduate level across the U.S. Most often, engineers enter the field with expertise in a major field of engineering, such as metallurgy. For the most part, biomechanics are employed in departments of orthopaedics across the country (9).

Early research was devoted to finding better and stronger materials from which to make joint replacements. The surge in joint implantation outpaced knowledge of joint mechanics and physiology, however. Therefore, investigation began on the biomechanical properties of bones, cartilage, and ligaments. Biomechanics have gathered information about these tissues both when healthy and when diseased. This knowledge has had critical importance in the search for better implant designs and implantation techniques, because the success of artificial joints depends heavily on the integrity of these tissues (9).

Many of the techniques employed by bioengineers in their investigations are borrowed from other fields in engineering. Some techniques are from the aerospace or civil engineering areas. For example, methods have been devised to analyze, prior to construction, stresses placed on skyscrapers so that they can be designed and planned properly. Similar "stress-analysis" can be used to understand structural stresses placed on the musculo-skeletal system. Such analyses are being done on the body with and without artificial joints in place. Information about the interactions between implants and the body are becoming available. In recent years that knowledge has been applied to improve the design of joint implant devices (9,77).

Throughout the era of joint implantation, biomechanics have 'bench tested' joint implants. Machines have been built that can grossly imitate the motions around the hip or knee and solutions have been concocted to imitate the chemical composition of the body's fluids. Tests have been conducted to correlate the data derived in the laboratory with actual results later obtained in patients. Unfortunately, many factors cannot be adequately controlled in the lab. One important factor is the variability in the skills of surgeons implanting the replacement joints. Another is the particular way each and every artificial joint recipient uses or abuses the replaced joint (69,82).

The only way to definitively determine whether or not a device is useful and/or successful, is to place it into people. The ultimate test is the years of use given those joints by recipients. Therefore, alongside physicians and therapists, bioengineers have begun to evalute patients in clinics. This has given engineers first-hand appreciation for both the problems and the successes of a particular joint (9).

An important endeavor for bioengineers is the analysis of used devices removed from patients, whereupon chemical, physical, and wear analysis can be performed to determine changes that have occurred (71). Implant retrieval analysis is important not only to the bioengineers and surgeons but also to attorneys and juries hearing cases of implant failure. A discussion of implant retrieval can be found Chapter 4.

Bioengineers are an integral part of the artificial joint implant development team. Today, most new designs for artificial joints are executed in collaboration with these scientists.

Manufacturers

The orthopaedic implant industry traces its origins back over one hundred years. The first firm to produce products for use in orthopaedics was DePuy Inc. Since that time numerous firms have been formed, bought, and sold. Because orthopaedic implantation is closely linked to metallurgy and progress in metal sciences, the predominant firm of the 1930's and 1940's was Austenal Laboratories, which owned the proprietary rights to medical-grade Colbalt-Chromium (Co-Cr) alloys (Vitallium). Other manufacturing firms acquired Co-Cr from the aircraft industry, modifying it to suit the needs of orthopaedics (83).

At present, there are 12 firms directly involved with the manufacture and sale of orthopaedic implants including artificial joints. Some are also marketing surgical appliances and hospital equipment as well. These firms (tab. 1) have all been in existence for variable lengths of time. Many (8 of 12) are subsidiaries of larger firms. Most of the mergers have taken place in the past 15 to 20 years. The industry claims that these mergers were necessary to off-set increasing business costs: government regulations (the 1976 Amendments) and high insurance costs. Also, the expertise of the larger

Table 1

Profile of the Orthopaedic Joint Implant Industry

COMPANY NAME	PRESENT OWNER	FORMER NAME
Biomet, Inc.	self-owned	formed in 1978
DePuy, Inc.	Behr-Manheim	DePuy, Inc.
Cintor	Johnson & Johnson	Codman & Shurtleff
Hexell, Inc.	-----	Hexell, Inc.
Howmedica, Inc.	Pfizer, Inc.	Austenal Laboratories
MedaTech	3-M Company	MedaTech
Orthopaedic Equipment Company (O.E.C.)	self-owned	Zimmer-G.B. (Great Britain)
Ostionics, Inc.	Stryker, Inc.	Ostionics, Inc.
Richards, Inc.	Rohr, Inc.	Richards, Inc.
Warsaw Orthopaedics, Inc.	self-owned	------------
Wright-Dow Corning	Dow-Corning, Inc.	Wright, Inc.
Zimmer-USA, Inc.	Bristol-Meyers	Zimmer-USA (United States)

firms in marketing and in dealing with the Federal system proves advantageous. Finally, the mergers allow the orthopaedic firms to raise large amounts of capital for new ventures, which are especially more costly in the presence of the Medical Devices Laws. DePuy Inc., Howmedica Inc., Richards Inc., and Zimmer Inc., currently dominate the Orthopaedic industry commanding nearly 75 to 80 percent of the national market (83).

The implant industry aims its efforts at helping surgeons meet the needs of their patients while remaining profitable. The role of the industry in the research and development of implant devices has been referred to as little 'r' and big 'D' (R & D) (81). That is, the basic research and testing of a new implant design is usually done by surgeons and bioengineers in the labs, and manufacturers are rarely involved in those early stages (little 'r'). The industry's task is to take the device from the drawing board or prototype stage, and put it into full-scale commercial production. The industry tackles the development problems of mass-producing such devices, closely cooperating with the designers as they progress (big 'D'). The wealthier firms may engage in early basic research on a device if they can afford it. In more recent years, manufacturers have begun to sponsor such activities outside the manufacturing plant (3,31).

If a manufacturer is interested in an implant design, arrangements are made with the designers over proprietary rights. In many cases, contracts made between manufacturers and designers are conducted after disclosure agreements are made. Patents and proprietary rights are negotiated, and on occasion the names of prominent surgeons will be associated with devices (81). However, such associations do not permit arbitrary assumptions about the financial arrangements made for the use of those names (3).

A major concern to companies in considering an implant for introduction is its development costs and its marketability. The recent enactment of the Medical Devices Act has altered those costs. Since marketability is intimately related to estimates of development and the final price of the device, these issues will be discussed in detail in the section on the Food and Drug Administration (FDA) in Chapter 9 and in Chapter 11.

Surgeons and/or bioengineers are hired by some firms as consultants for the purpose of commenting on proposed devices and their ability to perform. Such consultants may discuss the potential usefulness of such implants and their appeal to surgeons (3,31,54).

Manufacturing engineers supervise the development of the device in close consultation with the designers. They often become the liason between the company and the design team and they meet with designers in order to better understand the problems addressed by the implant and to discuss production problems. In many instances, engineers will observe surgeons in the clinic as well as in the operating room to gain the necessary appreciation of the surgeons' problems. In many cases, the manufacturing engineers will also be present at management meetings to explain progress on the implant project (3).

If companies lack the expertise to perform certain steps in the manufacturing process, they acquire the technology, contract others to supply it, or forego the implant entirely. The final developmental costs of the implant dictate such decisions (3,31,54). At present, only one company, Howmedica Inc., has the capability to cast its own devices. The other firms contract to have such castings supplied from foundries. Similarly, sterilization services are contracted for by all the implant manufacturers (83). DePuy Inc. recently introduced a new line of hip replacements featuring a new surface on the intramedullary stems which may eliminate the need for cement. The technology to produce this new surface was acquired by DePuy (3). Acquisitions are made by firms in order to offer new materials and processes for implant designers to consider. Many times, surgeons are not aware a material or process is available to them until they approach these companies with a design (9).

Before an implant product can be released to the market, it requires approval from the FDA. In the meantime, the marketing groups prepare packaging and advertising for new products and the sales forces are exposed to the products. With FDA approval, the devices are put into full-scale production, along with all the support products that may accompany it, such as surgical instruments. It may be of interest to follow a device as it proceeds through the production line (A).

The foundries supply Cobalt-Chromium alloys (Co-Cr) pre-cast, and Titanium alloys as bars. They comply with standards for these materials required by the FDA established by the American Society for Testing and Materials (ASTM). A certificate of compliance is supplied by the foundry with each shipment of material. When the raw material arrives, the manufacturers quarantine it so that it cannot be inadvertently used in the production line. The company will verify the identity of the metal and the certificates accompanying them. The firms will X-ray castings to insure no bulbs have formed inside the metal. In general, the larger the firm, the more elaborate the procedures taken to check the raw material. Zimmer-USA, the largest of the orthopaedic manufacturers, re-examines the physical and chemical characteristics of samples representative of the incoming batch. The results are then compared to the certificates supplied by the foundry. They reject less than one percent of the incoming material on that basis or because of casting inaccuracies.

Cleared materials are released for use on the manufacturing floor. As a particular hip or knee model is needed, the appropriate work order is drawn up. Each processing step is charted out on a flow sheet, as are logs of each step and quality control checklists. Blueprints are part of the work order packet, and any engineering modifications for that particular run are noted.

Co-Cr devices which arrive pre-cast require finishing to exacting standards by the manufacturer. The Titanium implants are machined and finished out of solid bars. Finishing and machining may require drilling, grinding, welding, polishing, and/or shining. These steps occur in different combinations and more than once for the same device. The devices must also be etched with the manufacturers part number and other identifying information.

After several processing steps are carried out, a quality control check usually takes place. Each individual part is carefully examined to insure that the work performed has met the design and engineering standards set for that part. Deviations from these standards can lead to production problems, or the final product may not perform properly once inside a patient. By checking production steps often, those devices which are defective can be eliminated early in the processing. The earlier a defect is found, the less is spent to finish that particular item. The FDA requires quality control procedures to be documented and kept on-file, including records of those devices which come off the production line. Much of the methodology used by these firms follows recommendations of the ASTM.

Upon completion of the device, a final quality control check is made of items: the device dimensions, its finish, and identifying markings. If satisfactory, the completed devices are then carefully cleaned of any particulate contamination, packaged, and labeled.

Labels for a production batch are made only at the time the devices are manufactured. Therefore, only the necessary number of labels are printed to match the number of devices to be packaged. Labels are double-checked for accuracy, and are packaged together with the device. This procedure is an attempt to insure that stray labels do not get placed on the wrong packages. The FDA has regulated the packaging and insert requirements of devices in the same fashion as drugs and many of the techniques for labeling are borrowed from the drug industry.

The device-filled cartons are shipped to a sterilization plant where they are subjected to radiation levels known to kill bacteria. Samples are contaminated with known amounts of bacteria before sterilization. These controls are sent for bacteriological study to verify the elimination of the bacteria. Manufacturers will quarantine the returned sterilized cartons until notification of successful sterilization is received, then the devices are made available for sale.

This industry spends considerable time and effort serving the custom-needs of its clientele -- surgeons. If a hospital or regional sales representative does not have the needed parts for an implant procedure, the firm involved will bend over backwards to get those parts to surgeons in time for surgery. If surgeons need a custom product for a patient with a peculiar anatomy or disease-caused deformity, the firms will make the part.

Surgeons may bring X-rays of a patient to manufacturing engineers and propose possible changes in a device to solve the problems encountered. Engineers will draw the custom implant and have the 'custom-shop' make the device. Such custom devices are usually costly and rarely result in a profit for firms. Yet, the service provided benefits the patients and, hopefully, the future sales of the companies as well.

Once a device and its surgical instruments are in production, the manufacturers still solicit improvements. A common instance involves a surgical instrument which does not suit the needs of a particular surgeon. Engineering changes may be introduced to a whole instrumentation line if a new idea seems good enough. However, the companies usually make a new instrument for a surgeon in the same manner that custom implant devices are produced. Many ideas for changes in the implant devices are offered to the manufacturers. Most are evaluated and discarded but those that are accepted are developed through a process similar to that of a new device. If successful, the changes may supplant the old device or the altered design will be added to the product line, thereby allowing surgeons to select the device they prefer (3,31).

The size of the firm dictates the degree of selection available. A small firm such as Biomet Inc. carries a line of devices that reflects their technological base in Titanium alloy production and they only manufacture well-known and successful hip and knee designs (54). A large firm such as Zimmer-USA, carries designs and models not in current use by many in the orthopaedic community. They try to serve the needs of all orthopaedists by maintaining a large and varied stock of devices, a service which requires a large investment (31). These two firms reflect not only differing marketing strategies, but the financial capabilities of the firms. This capability not only extends to marketing but also to research and development.

The smaller firms carefully and selectively evaluate device design proposals before embarking on development ventures (24,54). Larger firms may be more liberal when considering devices for production. They may invest in preliminary testing of a device design to learn more about it (3,31). However, the larger firms have not been leaders of innovation, rather the small firms have long held that role. Larger firms have tended to copy or purchase innovations or new technologies as they emerge. In the atmosphere of the Medical Devices Act, however, this past experience may change (37,630).

The role of the orthopaedic implant manufacturer in the technology of joint implants is central. These companies provide the materials and processes for manufacturing these implants for use by surgeons around the country. They help set high-grade medical standards for their products, and devote a great deal of effort customizing their services for surgeons. They consider numerous implant designs for mass-production and maintain inventories of devices, some long outdated. The ability of a firm to introduce new devices, maintain an inventory and acquire new technologies is largely dependent of its ability to finance these endeavors.

Man-Made Materials Used In Joint Implants: Their History And Present Use

Many compounds and materials have been tried as joint implants (B). The earliest included ivory, copper, gold, iron, and glass. Besides glass and ivory, which are fairly inert within the body, the other materials tended to corrode too quickly to be useful in long-term implant devices. In the 1930's, stainless steel was introduced. Drs. Jones, Houdack, and Murray demonstrated its biocompatibility with the body, and its suitability as a long-term material for use in implant (76).

Stainless steel has been used in orthopaedics since then and still remains a major material for many applications. Stainless steel can be made in a wide-variety of strengths and characteristics. It is economical, readily available, and there is a long manufacturing experience with it. But when compared with newer materials, stainless steel is prone to fatigue fracture. It will break after repeated stresses are placed on it, similar to circumstances normally found at the joints in the leg. Furthermore, stainless steel will tend to corrode after many years. Any defects on the surface of a stainless steel implant will permit corrosion to occur faster. Therefore, if a tiny crack develops in a joint implant, both repeated stressing, and corrosion will contribute to the eventual fracture of the metal at that site (82). At present, some very advanced alloys of stainless steel are being tested by John Charnley in England. Results of those studies are being awaited in this country for eventual applications to U.S. made artificial joints (9). Only one foundry now supplies medical-grade stainless steel (9).

Soon after the introduction of stainless steel, another alloy being used in dentistry was applied to orthopaedics. Drs. Venable and Stuck of Texas, suggested possible applications of Co-Cr to orthopaedic problems. They demonstrated the role of electrolysis in the deterioration of metals within the body and further proved that Co-Cr alloys were particularly resistant to such deterioration (76).

A casting company, Austenal Laboratories, had developed expertise in processing Co-Cr alloys and introduced Vitallium as their patented alloy for use in orthopaedics. Their rights to the alloy were suspended during World War II and Co-Cr has been generally available since then. As compared with stainless steel, Co-Cr has excellent strength properties but with its use in artificial hips it was noted that the alloy tended to fracture suddenly. Analysis of devices removed from patients led to improved manufacturing processes, all but eliminating the problem. The smooth mixing of the various metals comprising the alloy was found to be related to the sudden fractures, a problem existing in many metal-alloy processes. Newer manufacturing techniques have improved the even distribution of metals in medical-grade Co-Cr. Co-Cr is highly compatible with human tissues, although several cases of allergy to the alloy have been reported. Compared to stainless steel, Co-Cr is very difficult to machine and polish. It also is approximately 3 times more expensive than steel. Nevertheless, many total hip and knee replacements are made with Co-Cr.

Titanium alloys have been in use by European orthopaedic manufacturers since the 1950's. They have been introduced to the United States on several different occasions by different manufactures with mixed acceptance and success. One concern, Biomet Inc., bases a line of products on Titanium alloy (54). Of the alloys mentioned, Titanium is the strongest and the most corrosive-resistant and biocompatible. Furthermore, it tends to have the ability to bend without deforming or breaking, more so than either steel or Co-Cr. In this respect, Titanium is more similar to human bone, which has the same property to a larger degree. Titanium is readily machined, but cannot be cast. It is a difficult material to manipulate as compared with stainless steel, and like Co-Cr, it is fairly expensive to use. In high-stress situations, Titanium is the best available man-made material presently known and is particularly suited for hip replacements.

Polytetrafluoroethylene (Teflon), was the low-friction material used with metal to provide a low-friction bearing upon which the metal hip joint rests. During the first years of its use, Charnley quickly realized that this plastic was not strong enough to withstand the forces generated in the hip (13,15). After a short time, other polyethylenes were tried, all having higher densities. Finally, ultra-high density polyethylene (UHD-polyethylene) was used with success (9,77). At present, this plastic is either machined or hot-molded into shape. It provides a low-friction surface upon which a metal counterpart can slide. With time the plastic tends to deform under the stresses placed on it and a search for better materials is in progress. One material introduced in the mid-1970's has carbon fibers mixed into the polyethylene. This carbon-impregenated UHD-polyethelene is manufactured by Zimmer-USA and may prove to be superior to lone polyethylene (31).

The last material category presently used in joint implant surgery, the grouting agent, which evenly transfers the stresses from the metal of the prosthesis to the surrounding bone, is filled by polymethyl methacrylate (PMMA). PMMA is an acrylic polymer, closely related to the key ingredient in 'crazy-glue.' Prior to its introduction to orthopaedics, it was used in another form as Cranioplast to fill defects in the skull during neurosurgery. PMMA comes as a powder for mixing with a liquid catalyst. When combined, the slurry changes from a thin paste to a hard cement over a time period which can vary depending on several different factors. The chemical reaction liberates heat in proportion to the speed with which the cement sets. The faster the set, the hotter the cement gets. It is this characteristic which delayed the introduction of PMMA to orthopaedics. Cements such as Cranioplast were unsuitable for use within bone in large amounts, because the heat generated killed the surrounding tissue. The cold-curing cements do not get as hot and are currently being used in most implant surgery.

Chapter 4
A Historical View of Artificial Joints

4. A HISTORICAL VIEW OF ARTIFICIAL JOINTS

The concepts leading to the development of the modern era in joint implantation technology did not appear overnight. In recognition of this fact, the upcoming section briefly reviews the historical highlights in the development of these devices. As is the case with most scientific endeavors, the "breakthrough" represents the culmination of the years of contributions made by numerous people. In the case of joint implants, Sir John Charnley an orthopaedist and engineer, assembled the knowledge of his day and added the missing links, thus entered the modern era of artificial joint replacement.

The Hip

Diseases of the joints have probably plagued mankind since the beginning of time (C). As medicine increased in its sophistication, the various types of arthritis became the concern of internist/rheumatologist and the orthopaedist. Internists treat joint diseases with medicinal therapies aimed at improving the course of the disease process. In modern times, such therapy has been a combination of treatments aimed at relieving pain, as well as methods for reducing the inflammation in the joint surfaces. On the other hand, orthopaedists have physically altered the joint in order to reduce pain. Until the recent past, little was done to restore normal function at the joint.

The evolution of artificial joints can be summarized by pointing out that each device used was similar to one previous to it, with some additions and/or deletions. Changes in hip replacements have been progressive, the ideas for new devices based on the experiences with the old and the imagination of the designing surgeons.

Early attempts to restore function at the hip are based on the concept of resurfacing the joint. Theophilus Glick, a Bulgarian surgeon, in 1891 suggested interposing ivory between the adjacent surfaces of the hip. He also proposed to attach the ivory to bone with intramedually stems and a variety of cements such as plaster of Paris and pumice. These concepts, intrameduallary stems and cement, were far ahead of their time. As understanding of materials, body tissues, and surgical techniques improved, attempts were made to coax irregular, diseased tissue linings of the hip to smooth-out, thereby lessening pain and improving motion. Drs. Smith and Petersen began experimenting with glass cups placed over the head of the femur. The glass acted as a mold for scar tissue formation, the hope being that the resulting tissue layer would be a low-friction surface that was also pain-free. Early glass materials proved weak, and it was not until 1933 when Pyrex glass was used, that better results were achieved. Smith and Peterson reported good results with the device for up to two years.

In 1926, Dr. Hey Groves tried to completely replace the diseased femoral head. He had the artificial head made from ivory which he inserted into the femoral neck. This prosthesis was then fixed into place with ivory nails. It was used on only a few patients with generally 'poor' results. This marked one of the earliest attempts at removing a diseased portion of the joint and replacing it with a component totally artifical and man-made.

In the late 1930's, both Drs. Smith and Petersen, as well as Drs. Venable and Stuck introduced Vitallium (Cobalt-Chromium) for use as femoral head cups. Dr. Aufranc in 1957, reported his experience with 1,000 consecutive cases noting that many of them obtained satisfactory results. He stressed the fact that time was required for scar tissue to form, as well as for tissues and bone to heal. Therefore, rehabilitation and careful postoperative care were critical if satisfactory results were desired. The ease of insertion and simplicity of design popularized the femoral cup for use in patients where joint fusion was the only recourse left. Cup arthroplasty became the treatment of choice for end-stage degenerative arthritis until it was superceded by the Charnley total hip replacement.

The difficulty of guaranteeing good results with the cup arthroplasty fostered continued interest in complete replacement of the femoral head. Dr. Philip Wiles of London successfully devised a stainless steel femoral head bolted into the femur bone with screws. Other similiar replacements were designed on a custom basis by enterprsing surgeons. In all these instances, though, only a small number of devices were made for use in but a few areas. It was not until 1947 that the feasibility of a femoral head replacement caught the attention of the general orthopaedic community.

The Judet brothers, both French surgeons, introduced a femoral head replacement constructed of acrylic. The prosthesis could be viewed as a sphere attached to a thumbtack (13). A stainless steel rod encased within the acrylic was added to the stem after early all-acrylic devices broke. The Judet brothers reported the results of 300 consecutive cases in 1950, with followups of their patients as long as three and a half years after implantation. Compared to results with the cup arthroplasy, the Judet hip seemed better. The prosthesis was soon introduced in the U.S. in Vitallium rather than acrylic. Controversy swirled around the usefulness of the Judet device both here and abroad. The prime cause of failure of this device, as well as others that proceeded it, was losening of the stem of the prosthesis within the neck of the femur. As was the case with the cup arthroplasty, the Judet prosthesis was not perfect, but many people derived years of satisfactory service from hips that would have been fused otherwise.

Hip designs using intramedulary stems for support of an artificial femoral head appeared in the late 1930's and 1940's. In 1949, Dr. McBride introduced such a device and soon after, other similar designs appeared. Of the many devices available, one of the most popular was one devised by Dr. Austin-Moore. This device was driven into place within the femur's intramedullary canal and the artificial femoral head was made to the same size as a normal acetabulum, 42 mm, because it was intended for use in the intact acetabular cup. In cases where the acetabular surface was intact and disease-free, results with the Austin-Moore were good. However, in hips suffering from a degenerative disease it often led to poor results, as compared with cup arthroplasty. It soon became apparent that the Austin-Moore and similar devices were not adequate for the task of treating arthritis affecting both surfaces of the hip joint.

Besides failures due to diseased acetabulums, the Austin-Moore suffered the same problem as did the Judet prosthesis. Failures occurred because the device loosened within the femur. Contact between the metal stem and the bone was not evenly distributed over the entire stem. Instead of bone growing around the device and anchoring it, the bone resorbed under the stresses transmitted from the metal stem. A method not yet available was needed to uniformly distribute the stresses on the artificial hip along the anchoring intramedullary stem.

In 1951, Dr. Edward Haboush of New York devised a hip replacement that tried to overcome the problems of the Austin-Moore device. He made replacements for the femoral head and the acetabular cup, and he experimented with Craniplast , a polymethyl methacrylate (PMNA) cement. Results of his few operative attempts were poor because of the difficulties he encountered.

It remained for Sir John Charnley to integrate the knowledge accumulated about artificial hip replacement, as well as his own insight, in order to design the successful total hip replacement. Charnley noted that patients with the Judet hip squeaked soon after they resumed their activities following surgery. Understanding that this resulted from friction between the device and the acetabulum, he reasoned that the squeak stopped after the Judet hip froze in the acteabulum. Therefore, motion around the hip joint was a function of the Judet hip loosening in the femur, rather than the femoral head pivoting in the acetabulum. Charnley investigated the frictional characteristics of the hip in animals and found that the hip joint was 100 times more slippery than a skate on ice. He recognized that this was unattainable with modern materials and engineering, and settled on the best low-friction material he could find that was compatible inside humans, polytetrafluoroethylene, otherwise known as Teflon . At first, he used thin layers of Teflon on both sides of arthritic joints, but the degree of surgical manipulation required to secure it into place led to the death of the underlying bone (13).

Charnley decided that complete replacement of the femoral head was needed. In conjunction with a dentist, Charnley began work with a cold-curing cement made of PMMA. Besides learning how to manipulate this material, he added Barium Sulfate to it, thereby making it visible on X-rays. He proposed to use PMMA as a grouting agent, evenly transferring the stresses from the metal stem of a prosthesis to surrounding bone (13).

To further reduce friction in the replacement hip, Charnley modified the Austin-Moore prosthesis. He reduced the femoral head size (and therefore the surface area of the head) from 42 mm, to 22 mm, thereby lowering the friction of the head, which pivoted inside an artifical acetabular socket made with a surface of Teflon (13).

Charnley reported his innovations and early surgical experiences in 1961 in a small article in the British Journal, Lancet (13). Charnley continued to refine his surgical techniques and used longer lasting low-friction polyethylene materials (UHD-polyethylene) in the acteabular cup, instead of Teflon. In the next few years, the orthopaedic community watched closely to see if Charnley's ideas and concepts would withstand the results of the long-term use of his device by the recipients. Once the results of his replacements indicated success far better than ever achieved previously, the era of modern joint replacement was born.

The Knee

The simplicity of the hip joint accounted for much of the enthusiasm demonstrated by surgeons trying to devise replacements. In contrast, the knee, by far the most complex of human joints, was only tinkered with. There was a poor understanding of its mechanics and the interactions between its ligaments, muscles, and bone. The early approaches to knee replacement mimicked that of the hip. Materials and designs that could resurface the femoral condyles or the tibial plateau were sought. Dr. McKeever devised a prosthesis for the knee-cap (patella) in 1949, thus preserving function of the important quadricep muscle group in the thigh. This device was satifactory and was an early successful replacement operation in the knee.

Even though many sporadic attempts were made at restoring the knee during the late 1930's and 1940's, it was not until 1950 that productive designs appeared. The French surgeon, Walldius, designed a hinged knee device made of acrylic. After eight years of experience, Dr. Walldius reported good results in 64 percent of his patients and found that failures were often due to wear of the acrylic. These failures eventually led him to use Vitallium instead of acrylic. A number of different hinge knee devices are available today, but normal knees do not function as hinges, therefore, such devices are not capable of fully returning patients to many activities. The hinge knees have always been controversial, yet they remain popular in Europe and in areas of the U.S. Many orthopaedists regard them as a last ditch effort to save a knee from permanent fusion.

Other surgeons in the 1950's searched for better ways to resurface the knee. Dr. McKeever, and Dr. McIntosh soon thereafter introduced a tibial plateau prothesis. The McIntosh design originally was constructed of acrylic. The device was a thin plate, placed over the diseased tibial cartilage, on which the femoral condyles could pivot. Compared to the Walldius knee, this device was extraorinarily simple in design, and easily put into place. Problems with wear of the plates lead to a series of material changes, until Vitallium was used in 1964. A variety of different plates were offered, to insure a good 'fit' for many knees. In part, the popularity of the plate arose because of the care Dr. McIntosh took to define the uses for his protheses. The tibial plateau prosthesis became an alternative treatment in cases of tibial disease in which the knees were not severely deformed.

Devices were also introduced to resurface the femoral condyles. These were made of stainless steel and placed over the diseased femoral condyles (ig 2). But all the knee prostheses introduced suffered from similar problems. Infection rates, especially for the Walldius replacement were high. Correct alignment of the femoral, or tibial prothesis proved to be difficult and incorrect placement led to premature wear and failure. Finally, these devices tended to become loose because of resorbtion of the underlying bone.

The knee devices designed did not address complexities of knee anatomy or geometry. Designs were created that seemed intuitively correct but only limited success could be hoped for until a better understanding of knee biomechanics was obtained. The catalyst for the explosion of knee prostheses was the apparent success of the Charnley hip in the 1960's. The introduction of PMMA as a grouting material, the use of metal sliding on polyethylene components, and the slow infusion of engineers into orthopaedics research played a role for the emergence of knee replacements.

Chapter 5
The Modern Era of Joint Implantation: The Evolution of the Artificial Knee

5. THE MODERN ERA OF JOINT IMPLANTATION: THE EVOLUTION OF THE ARTIFICIAL KNEE

The renewed effort to develop other artificial joints, after the demonstrated success of the Charnley hip, is well exemplified by the rapid introduction and wide use of artificial knees. The section to follow is by no means a complete review of each and every knee joint designed and brought to the market in the 1970's. Rather, it highlights the principles introduced in these joints, and the way clinical results have been used to assess the designs put forth. The descriptions of the devices discussed are coupled to reports found in the literature on their performance in recipients. Changes in knee designs have been made based on surgical experiences and/or patient experiences, often before sufficient quantities of cases could be accumulated for formal analysis (9).

In looking at the development of the knee, there appears have to been three distinct phases in thought and design of knee prostheses. This chapter traces the changes of several representative knee designs through the successive generations. The first generation spans from about 1966 to 1970 and is exemplified by the Gunston or polycentric knee. The second generation spans from 1969 to 1972 and is traced with the geometric and duocondylar knees. The third generation is represented by the anametric and total condylar knee systems. It becomes evident that there is a convergence of design features, as principles and concepts are tried, tested, and proven in the laboratory and in the recipients. At present, the most advanced knees available are improvements on the third generation devices (9).

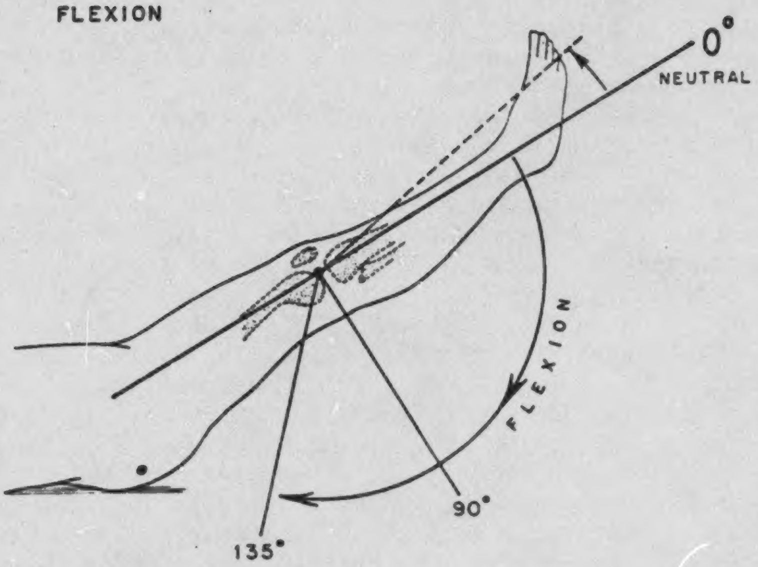
Before embarking on the discussion on the evolution of knee joints, it may be useful to mention several facts concerning knee biomechanics, only clearly elucidated within the past 20 years. The normal knee has a range of motion (ROM) of almost 140 degrees (see fig. 3). It transmits loads, aids in the conservation of energy during motion, and is an active participant in motion as well. Studies have shown that the average ROM of the tibia in relation to the femur is 93 degrees. Walking on a flat surface requires about 67 degrees of motion. Lifting an object while bending at the knees requires motion at the knee of 117 degrees. The knee absorbs considerable amounts of force. Walking on a level surface transmits over 3 times body weight through the knee. Climbing stairs requires the knee to withstand forces over 4 and one quarter times body weight (27).

The knee can perform in many other ways besides those mentioned. Its complexity can only be inferred from this short description. But the versatility of the knee and its ability to absorb forces and stress far in excess of body weight is testimony to the difficult task undertaken by orthopaedists and bioengineers in developing adequate replacements for it.

Artificial Knees: The First Generation

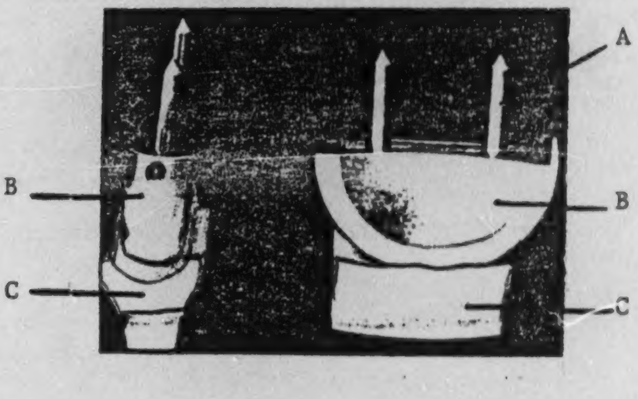
One of the earliest knee replacements, which appeared in the mid 1960's, was the polycentric knee designed by Frank Gunston. As a student of Charnley, he was in an excellent position to take advantage of Charnley's concepts. This prosthesis (and all of its later variants) consists of four separate parts. Two semi-circular runners are cemented to the femur. The tibia is notched to accept two polyethylene runners intended to mate with the metal runners above (see fig 4) (33).

Figure 3
The Range of Motion of the Knee


FLEXION
0°
NEUTRAL
FLEXION
90°
135°

Reprinted with permission from: Gartland, J.J., Fundamentals of Orthopaedics, W.B. Saunders, Philadelphia, Pennsylvania, 1979, p. 408.

Figure 4
The Gunston Knee Prosthesis



A. Pins for insertion into bone and alignment.

B. Semi-circular runner attached to femur.

C. Polyethylene runner for insertion into tibia.

Reprinted with permission from: Clinical Orthopaedics and Related Research, 94:129, 1973.

The device as designed by Gunston did not use intramedullary stems to fix the tibial component into place. Only small amounts of bone had to be removed to place the device. The prosthesis was intended for use in patients with well preserved knee ligaments not deformed by disease. Furthermore, the device's design depended on those ligaments to provide stability to the recipients (33).

The polycentric knee was introduced in the U.S. by Drs. Bryand and Peterson of the Mayo Clinic. At first, Dr. Gunston supplied the knee devices from Canada. Later, the prosthesis was manufactured at the Mayo Clinic. Between 1970 and 1973, 350 cases using the polycentric knee were recorded at the Mayo Clinic. Reports on the early polycentric knee showed that of 350 cases done, there were 35 (10 percent) complications, of which 25 were directly related to the device itself, not the surgical stress. Six knees suffered from deep infection, 3 of which could not be treated adequately requiring removal of the prostheses. Within 7 months, 3 devices had loosened sufficiently to require re-operation. Of those that did not suffer early demise from complications, over 30 people progressively lost 'excellent-good' functioning of the joint in the first 2-year period (6). Later reports from the Mayo Clinic showed that the number of people losing function of their knee doubled to 61, with the marked increase in functional losses occurring after 5 years of use. Therefore, over the 7-year period, 36 percent of those joints that did not fail due directly to complications, deteriorated and provided unsatisfactory function (5).

Of course, the findings after 7 years could not be anticipated in 1973. Other problems were already evident with the Gunston device. Devices which had to be removed, whatever the reason, were exhibiting unusual and excessive wear on the polyethylene tibial grooves. This proved strong evidence that alignment of the device, and its design were not adequate for the task of restoring knee function. The forces acting through the knee, and the surgical difficulties of aligning the device's four separate components, greatly concerned surgeons who were using the device at the Mayo Clinic and elsewhere.

Another knee prosthesis devised in England has been available in the U.S. since the early 1970's. Designed by Drs. Freeman and Swanson, it is currently called the ICLH Imperial College and London Hospital knee. The ICLH knee in all its forms has never been widely accepted in the U.S., but several of its features influenced designers in this country (9,77).

Freeman and Swanson were cognizant of the knee alignment problems inherent with the designs available, such as the polycentric design. Furthermore, they believed that disrupting the cruciate ligaments of the knee was not the death knoll for knee stability when using a non-hinged device. In designing their knee, Freeman and Swanson intentionally sacrificed the cruciate knee ligaments, thus allowing them to sculpt the femur. This permitted a U-shaped femoral component to be easily aligned and fitted on the femur. The stability sacrificed with the ligaments was restored by the shape and configuration of the knee device (29).

Artificial Knees: The Second Generation

Introduced in 1971, the geometric knee system, and its variations by others, was originated at the Mayo Clinic under the direction of Dr. M. Coventry. He and five other orthopaedists were dissatisfied with the polycentric design. They undertook to improve knee prostheses and widen the types of patients treatable with a nonhinged device (20a). They reduced the number of implanted components from four to two. Instead of separate femoral runners, a connecting bar was placed across the femoral component. Similarly, they added a bar across the polyethylene grooves used on the tibia (see fig 5). They designed the device so that the cruciate ligaments of the knee could remain intact for optimal knee function. Finally, the geometry of the components added stability to the knee, a characteristic referred to as constraint. This feature provides stability to the knees of those people who had less than perfect ligaments and/or knee deformities due to their arthritis (20a).

The device was designed in conjunction with Howmedica Inc., and modifications were made to the device during several stages of development both before and after it was introduced. The U-shaped underside for the femoral component, similar in some respects to the concepts of the ICLH knee, was incorporated. Further changes in the underside of the tibial plateau were made to improve its stability and its attachment to the underlying tibial bone (20a).

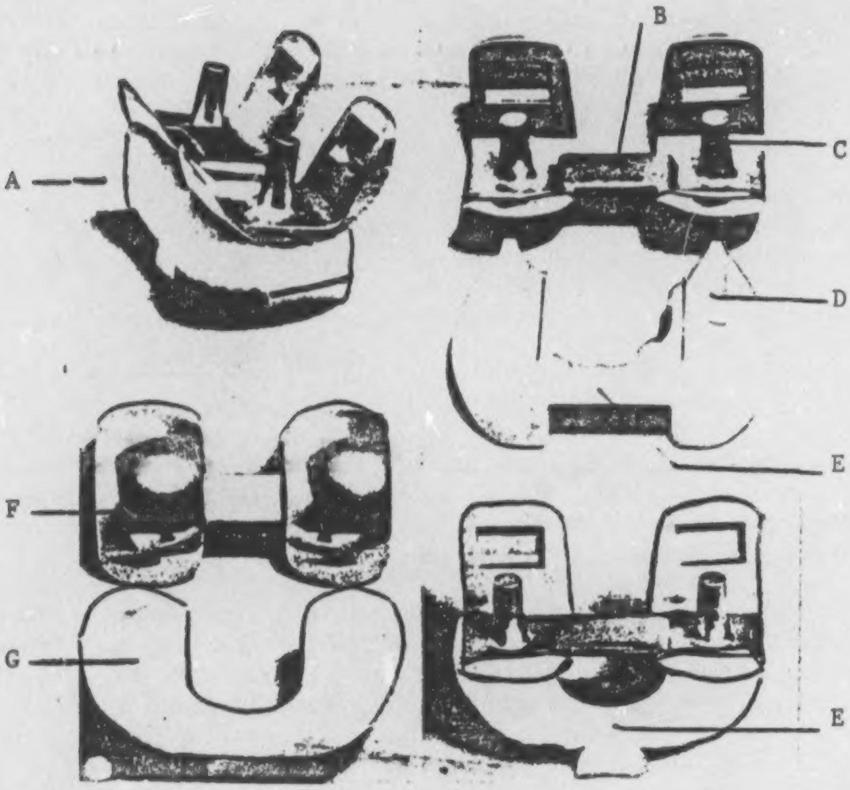
At the time the geometric knee appeared, work was underway at the Hospital for Special Surgery (HSS) on another knee system. Under the direction of Drs. Insall and Ranawat, and Dr. P. Walker a bioengineer, the condylar knee system was introduced. In many respects, the unicondylar device was similar to the geometric design (58,77).

The unicondylar design was a variation of the polycentric knee. Recognizing the problems of aligning four components, the HSS group also made a duocondylar model. Thus, the unicondylar design could be used when only one compartment of the knee was damaged and the duocondylar design used for the bicompartmentally-diseased knee. The duocondylar prosthesis was really two unicondylar models placed side by side with an attachment running across, similar to the geometric design (9,77).

However, there are several distinct disimilarities between the duocondylar and the geometric designs. The femoral runner of the geometric design was not intended to be anatomically correct by the Mayo group (20a). On the other hand, Dr. Walker and the HSS bioengineering laboratory reproduced and studied the anatomical load characteristics of normal femoral condyles. They incorporated some of those finds into the design of the condylar prosthesis (78). Another difference was the underside of the femoral parts. The geometric design used the U-shape to ease alignment difficulties. The duocondylar design still used pins on an unaltered femoral bony end. Finally, the geometric knee was intended to provide more constraint to the knee of the recipient but the duocondylar was almost totally unconstrained.

In some respects, the polycentric, ICLH, geometric, and condylar knee systems were the backbone of modern total knee systems used today (9). When these knees were developed, few performance parameters could be predicted in the laboratory. The knees were not life-sustaining nor life-supporting, so lethal catastrophies were not expected. Surgical techniques and surgical tools could be tested on the knees of cadavers, but as Dr. Coventry later wrote, "Instrumentation was somewhat imprecise, and the many aspects of (the surgical) technique(s) ... had to be found mostly through trial and error"

Figure 5
The Geometric Knee Prosthesis



Tibial Component

A. Side view.

D. Dovetail pins for fixation of the component to the bone with cement.

E. Crossbar connecting both tibial runners.

G. Articulating surface of tibial component.

(20). However, several parameters could be predicted in the lab. They were: range of motion, inherent joint-implant stability (or constraint), and the expected life of the joint under loads similar to that found within the knee of a person.

Other aspects that were examinable but not necessarily predictable included the ability of the joint device to perform if placed in a less than perfect alignment and material deformities occurring under stress. For such tests, cadavers and knee simulators were used. The latter were mechanical contraptions, often computer-linked, which grossly imitated the motions and forces exerted around the knee by the body. The data used to design such simulators had been accumulated by bioengineers since the 1950's. A joint could be mounted with bone and cement on the simulator for repeated cyclic testing. But, even with laboratory data it took several years for the condylar system and the geometric system to establish their own track record for success and performance in people (66).

By 1973, 317 geometric knees had been implanted. The knees treated were almost evenly split between those afflicted with osteoarthritis and those afflicted with rheumatoid arthritis. The ratio of men to women was one to two. Because several years must pass before evaluation of data on the joints and their performance can be done, it was not until 1974 that enough knees had been implanted and watched (68). This report was based on 119 knee replacements done between 1971 and 1972. In 100 of those cases, relief of pain was the primary goal of the surgery. In the other 19 cases, severe knee deformities or poor knee function were the indications for replacement. The average age of the recipients was 61 years old and 57 of them had previously undergone another procedure on the diseased knee. The questions which needed to be addressed included: What was the correct selection of patients for the geometric knee? What were emerging problems with the design of the knee? And, what were the effects of changes in the surgical techniques used?

After a followup of at least two years, 102 patients were available for inclusion into this report. The surgeons noted that alignment and positioning of the two-part geometric system was easier and more consistent as their expertise increased, especially when compared to the polycentric (four-component) system. There were two deep infections requiring removal of the prostheses and subsequent knee fusion. Thirteen knee devices showed loss of fixation (loosening) of the tibial part (11.8 percent) (68), as compared to a loosening rate of 2.4 percent reported with the polycentric knee in another series of 500 cases followed for two years at the Mayo Clinic (67).

After two years, 92 percent of the patients receiving the knee reported little or no pain in the operated knee. The other 8 percent reported moderate to severe pain. Fifty percent of the patients walked with aids such as crutches or walkers, one person was unable to walk and the other 42 patients (41 percent) walked unlimited amounts, 58 percent walked between rooms of a house up to as much as 6 city blocks, and 3 patients could go from bed to a chair. Of the 102 cases reported, 10 were re-operated for loosening and 2 were re-operated for pain (68).

As compared to the results obtained after 2 years with the polycentric knee, the geometric knee appeared effective but with loosening occuring 5 times more often. Recall that data available after 5 to 7 years of use demonstrated the progressive deterioration of function in the polycentric knees.

The surgeons at the Mayo Clinic learned a great deal from these cases. They realized that loosening was partially due to components not being perfectly sized for patients with differing anatomical features. They also learned that the quality of the bone underlying the tibial part was very important for fitting and fixation. In response to these factors, they changed the recommended indications for the use of the prosthesis and the tibial component's undersurface to improve the fixation between polyethylene, cement, and bone (20).

The duocondylar and the unicondylar knees were introduced around 1971 as well and it took until 1974 to accumulate enough cases for clinical experience to show distinct trends. The Hospital for Special Surgery (HSS) tried to determine if indications for surgery were correct, whether there were design shortcomings, and tried to assess the results from improvements in surgical techniques. Sixty knees treated with the duocondylar unit were followed for at least 2 years. Simultaneously, 50 geometric knees were also followed for comparison, all implanted by the surgeons at HSS. Unlike the cases in the Mayo Clinic study, which were evenly divided between osteoarthritis and rheumatoid arthritis, the HSS cases were predominantly (70 percent) rheumatoid arthritis (41).

The knee device evaluation system used at HSS was different from the one used at the Mayo Clinic, and reported on function based on many parameters, not directly comparable to the Mayo Clinic determination of walking distances earlier reviewed. After two years, 86 percent of the duocondylar recipients reported little or no pain, while 84 percent of the geometric recipients reported little or no pain; 36 percent of the duocondylar recipients had 'excellent' functional results with their replaced knees, but only 8 percent of the geometric knee had 'excellent' functioning; 28 percent of the duocondylar patients had 'good' results, and 48 percent of the geometric patients had 'good' results. Combining the two categories, 64 percent (39 patients) had 'excellent to good' results with the duocondylar knee prosthesis and 56 percent (28 patients) had 'excellent to good' results with the geometric knee. There were no deep wound infections reported. Three duocondylar devices were removed because of loosening, and follow-up X-rays of the replaced knees showed early signs of loosening in over 70 percent of the cases, but only 1 device had been removed at the time of the report (41).

Comparison with the Mayo Clinic results would not be valid because of the different criteria used. The HSS group noted problems with the geometric knee that were similar to those noted by the Mayo group as well as the shortcomings of their own device. Their results did not reflect problems with regard to patient selection, but with design and surgical problems that restricted subsequent patient function and the overall medical condition.

Artificial Knees: The Third Generation

Evaluation of the geometric and condylar designs led to another redesigning of the total knee joint (9,20,77).

Design and introduction of the duocondylar system began an effort at HSS to devise solutions to the problems of knee implant systems. Problems with these joints were becoming apparent to many surgeons using them. The surgeons and bioengineers at HSS set out to overcome those problems (77). Research in the bioengineering lab at HSS was being conducted on many facets of the musculo-skeletal system and on joints, supported for the most part with grants from the National Institute's of Health (NIH) (77). Some of the information collected in those studies was applied to the knee replacement system they designed.

The more obvious deficiencies in knee prostheses quickly attracted attention. Loosening of the tibial components was considered excessive and unacceptable at HSS. A loosening rate of 10 percent or more, two years post-operatively, was poor when compared to the results obtainable with total hip surgery (less than 1 percent). The recipients of knee prostheses usually did not undergo surgery of the patella. As many as 15 percent of 750 cases performed at HSS had patella pain after several years, which reduced the ability of many of these people to function well (42).

Just as disturbing, however though, was the limited application of the knee devices available. The indications for the non-hinged resurfacing devices were clear; only those patients with relatively intact and stable knee ligaments were obtaining good results with their new knees. Patients with poorer knee joints suffered more problems with them. The hinge knee devices were well known and were used in those cases that would otherwise go to knee fusion because of severe pain and major knee deformities. The potential of deep infections with the hinge devices and the large amounts of bone that were removed made such devices a last alternative in the minds of many surgeons (69).

The HSS research group set out to devise a number of closely interrelated devices which would overcome the problems outlined above. Not only was the problem of fixation addressed, but the devices were intended for application across a wide spectrum of deformed and diseased knees. Such a group of devices would also require another feature, as yet never attempted; a reliable, accurate, and usable set of surgical instruments with which the different models of a device could be implanted (77). Many practicing orthopaedists fought to improve surgical instrumentation accompanying devices. Instrumentation improvements often tended to be regional, reflecting the influence of prominent surgeons practicing in that part of the country. The new devices and instruments did not reflect a unified approach to re-designing the entire prosthesis (9,31,27,69,77). The HSS group realized that a comprehensive knee system would have to be designed from the top on down. Furthermore, a system consisting of three parts; tibial, femoral, and patellar components, had to include an accurate and reliable set of instruments for alignment and fixation (77,79).

Some of the research supported by the National Institute of Health (NIH) at HSS, included studies with experimental 'stabilizers' as substitute for the hinges. Such stabilizers provided a combination of freedom and constraint needed for stable and natural knee motion (79). Dr. Insall and his group were influenced by the concepts of Drs. Freeman and Swanson, and felt that the internal (cruciate) ligaments of the knee could be sacrificed without later functional losses (28). The combination of a stabilizer and removal of the cruciate knee ligaments formed the basis for the new knee design.

The concepts and principles established in the design of the femoral surfaces for the duocondylar devices (78) were retained in the new design. But the U-shaped femoral component undersurface was introduced, along the lines originally developed in the ICLH knee (9).

Biomechanical studies on the patella in normal and diseased knees provided the basis for a patella "button" to be used for resurfacing the underside of the patella. It was intended to be used as part of the total knee system (in polyethylene), as well as alone (in metal) for people with patello-femoral disease. A flange was added to the femoral component to articulate with the new patella button (fig 6) (1).

Work on the total prosthesis was conducted entirely within the HSS. Production of the device in all of its stages was originally planned with Codman Inc. and later with Howmedica Inc. Development of the surgical instruments was done mostly in the operating room and on cadavers, in conjunction with the manufacturers. In 1975, the Total Condylar Prosthesis (TCP) introduced (77).

The TCP consisted of three related sets of prosthesises. The first set (TCPI) was intended for those patients with non-deformed well-preserved knee ligaments but who suffered from severe pain. The second set (TCP II) was similar to the first except for the addition of a stabilizer tab on the tibial component, which provided a limited amount of added stability for those patients with mildly unstable and deformed knees. Finally, the third set (TCP III) had a large stabilizer tab on the tibial component for the high degree of stability and constraint necessary in people with severely deformed knees. All three units shared a complete line of instruments for the implantation of the devices (43).

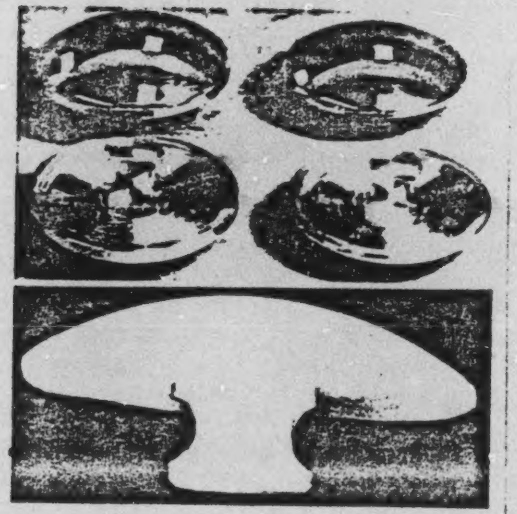
In spite of the research and testing of this design, the predictive limitations of the bioengineering laboratory remained the same. The only true testing ground for the TCP system remained the human body (9,77).

The difficulties and concerns expressed by the surgeons at the HSS were echoed by the surgeons at the Mayo Clinic. By 1975, there was interest in improving the performance of the geometric knee. Between 1972 and 1976 the number of knee replacements increased an estimated seven-fold (39). The dialogue between practioners, and the upswing in the research being conducted at the Mayo Clinic and elsewhere, contributed to the perceptions held by Mayo Clinic research group.

The problems identified with the geometric knee were summarized by Dr. Coventry as follows: 1) excessive loosening of the tibial component; 2) the geometric design did not provide an adequate range of motion to accommodate the activities of daily living; 3) an increase range of motion required improved stability and constraint compared to that in the geometric knee; 4) a patella replacement was needed to relieve patellar pain and to improve muscle strength around the knee; 5) the cruciate ligaments of the knee were very important and should not be sacrificed, thereby maintaining good stability in the knee postoperatively (20).

The bioengineering characteristics and properties of the geometric knee system were investigated. Analysis of the stresses and loads placed on the

Figure 6
The Patella Button



Top: Dome shaped patella prothesis in 2 sizes.

Bottom: The plastic patella used in association with the Hospital for Special Surgery total knee, called the "total condylar knee".

Reprinted with permission from: Clinical Orthopaedics and Related Research, 107:175.

geometric knee were also conducted (12). Measurements and determinations were made of diseased knees in order to clearly define functional losses suffered by people with arthritic knees (35). As the newly designed knee was taking form, it was repeatedly analyzed and improved in conjunction with Howmedica Inc., who produced the device (83).

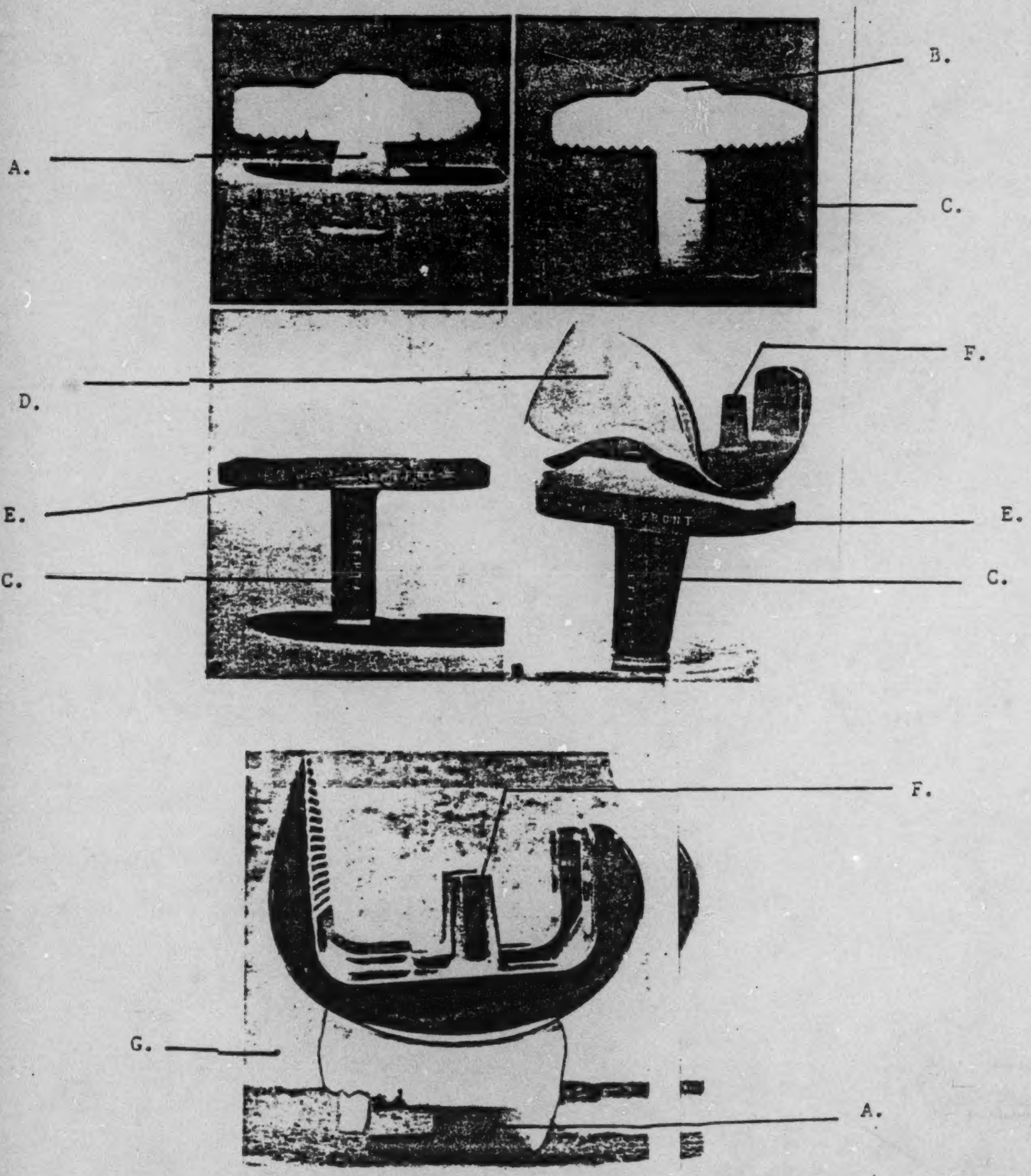
As had been the case in the past, this prosthesis intended to adequately reproduce the function of a normal knee. In 1977, the Anametric Knee system was introduced and with it came new features. The curvature of the articulating surfaces of the tibial and femoral components and were the undersurface of the tibial components changed to provide better constraint and function. The undersurface of the tibial component was altered again to improve its fixation properties to the underlying bone. A patella button was introduced as well as a flange on the femoral component to articulate with it. The U-shaped undersurface of the femoral component was retained for better alignment of the prosthesis. Finally, the surgical experience accumulated by the Mayo group was directed at improving the instrumentation for implanting the device (See fig 8)(20).

The Anametric and TCP knee replacements and subsequently improved models are currently available on the market. To a large degree, they all share features already described. As a matter of fact, revisions to the TCP design were introduced by several staff members of the HSS and are marketed by Zimmer-USA as the Insall/Burstein® total knee (9,31). While at Howmedica Inc., Peter Walker designed the kinematic Knee System®, an improvement upon the TCP system he helped pioneer at HSS (77). These two up-dated prostheses are but a small sample of the available total knee replacements on the market. Because these devices are relatively new, there is little data available in the literature on their performance in patients.

Between 1974 and 1978, the HSS performed 1201 TCP operations. However, only 461 cases were available for a report published in 1979 (42). Of those studied, 354 cases were implanted with the TCP I, 103 knees were TCP II devices, and 4 knees were repaired with the TCP III. The ratio of female to male recipients was four to one. The average age of the recipients was 65 years old. There were approximately twice as many knees afflicted with osteoarthritis as with rheumatoid arthritis (41,42).

The minimum followup for the TCP I cases was two years, one year for the TCP II and TCP III cases. In all: 312 knees (68 percent) were given ratings of 'excellent,' 109 knees (23 percent) gave 'good' results to their recipients, 18 knees were 'fair,' and 22 knees were rated 'poor.' The average range of motion for the repaired knees was 90 degrees (42). Complications accounted for 14 of the 22 poor knees; 6 knees suffered from deep infections, 2 of which could not be adequately treated medically, requiring removal of the prostheses and knee fusions. Three other patients were cured for their infections and were doing well. The last patient died from other causes. Six TCP I knee recipients had chronically dislocating knees, 4 of which provided poor function, 2 were revised and replaced with the more constrained TCP II models, with better results. The patella component loosened in 3 instances (0.6 percent) but only 1 was replaced. Seven tibial components loosened (1.5 percent), and 3 of those were revised. The remaining 7 poor case outcomes were attributed to pain of unknown origin of a very severe degree that prevented the recipients from functioning (42).

Figure 7
The Anametric Knee Prosthesis


B.
A.
C.
F.
D.
E.
E.
C.
C.
F.
G.
A.

Tibial Component

A. Dovetail pin for fixation of component to underlying bone with cement.

B. Tab on surface of component for extra stability (constraint).

C. Intramedullary stem for insertion into underlying bone with cement (metal or polyethylene).

E. Metal tray onto which polyethylene component is placed.

Femoral Component

D. Metal flange for patella button to slide on.

F. Orientation pin for alignment of component on bone.

G. Side view of components - note the U-shape of the undersurface of the femoral component.

Reprinted with permission from: Clinical Orthopaedics and Related Research, 145:32, 1979.

In comparison to the results obtained with the duocondylar or geometric knee at HSS, the TCP replacement knee seemed far superior; 36 percent of the duocondylar replacements reported 'excellent' results, as compared with 68 percent of the TCP knees, and only 8 percent for the geometric design. Combining the 'excellent-good' categories; the TCP knees provided 91 percent of those total results, as compared to 65 percent obtained with duoconcylar units, and 56 percent with the geometric prostheses. It would seem from these preliminary reports that the principles and knowledge accumulated in the bioengineering laboratory, the clinics, and operating room were having a marked effect on the performance obtained with total knee replacements (41,42).

The Anametric knee, which appeared later than the TCP has not been in use long enough to provide more than a 1 year followup. The most recent published report presents information on 112 knees. The average age of the recipient was 64 years old. The proportion of women to men was 2:1. The ratio of osteoarthritis to rheumatoid arthritis was 5:2. More detailed information on the epidemiologic characteristics was provided by the Mayo study group than needs to be mentioned in this summary (25).

There is a difficulty in presenting the results obtained with the Anametric prosthesis. This report uses a new system for evaluating Anametric knees, discarding the earlier system used to evaluate the polycentric and geometric knees. Nor is the new system the same as the one used at HSS. Results are divided by the type of arthritis treated, rather than as a summary of all the implanted knees. The system used in the report is a numerical scale from 1 to 10 for pain, function and walking. Ten is a perfect score and is a failing result. The table on the next page summarizes the evaluations of the 112 knees repaired (See tab 2 & tab 3) (25).

The problem of loosening was indicated by the evidence on X-rays. One patella showed such evidence in a rheumatoid knee, as did five tibial components. However, no revisions had been done. One femoral component indicated evidence of loosening on X-ray in the osteoarthritic knees repaired, as did 24 (30 percent) of the tibial componenets. However, no revisions of those knees had been done, either (25).

An interesting corollary to the results of the Anametric knee design is provided. Not all the knee recipients received patella replacements. Therefore, surgeons at the Mayo could evaluate the difference in pain between the cases that had patella replacement, and those that did not: 10 of 31 rheumatoid patients and 40 of 81 osteoarthritic patients did not get patella replacements. The osteoarthritic knees with replaced patellas had a post-op pain rating of 9.2, while the knees without new patellas had a pain rating of 8.2. For walking, the osteoarthritic knees with replaced patellas had a rating of 9.0, while the knees without the patellas had a rating of 7.8. The difference between the scores was considered statistically significant by the authors ($p < 0.01$). In the area of function, the replaced osteoarthritic patellas and knees had a rating of 8.6, as compared with the unreplaced patellas' rating of 7.5. The range of motion of the patella-replaced knees was 102 degrees, the range of the motion of the knees with unreplaced patellas was 100 degrees. The differences noted in these two categories was not considered statistically significant (25).

Table 2

Results of Anametric Total Knee Arthroplasty in Patients with Osteoarthritis

Criteria	Preoperative	Postoperative
Pain	3.2	8.7
Walking	4.5	8.4
Function	4.2	8.1
Flexion Arc	93°	100°

Reprinted with permission from: Clinical Orthopaedics and Related Research, 145:87, 1979.

Table 3

Results of Anametric Total Knee Arthroplasty in Patients with Rheumatoid Arthritis

Criteria	Preoperative	Postoperative
Pain	2.2	9.1
Walking	3.6	8.5
Function	3.1	8.3
Flexion Arc	91°	102°

Reprinted with permission from: Clinical Orthopaedics and Related Research, 145:87, 1979.

Chapter 6
The Medical Indications for Total Joint Replacement

6. THE MEDICAL INDICATIONS FOR TOTAL JOINT REPLACEMENT

During the course of many diseases which affect human joints, internists and/or surgeons may decide that an artificial replacement of that joint may be appropriate and beneficial (D). A list of medical indications is extensive; therefore, only highlights will be discussed. Diseases can be categorized under broad headings that divide the body into systems. The symptom common to many joint diseases is pain. This pain can become severe and untreatable with standard medical therapies and the primary goal of replacement of the hip or knee is eradication of this pain. The secondary goal is return of useful function at the replaced joint. Today, knee and/or hip replacement has become a treatment of choice when less drastic therapies and procedures have failed.

Two major diseases that afflict joints have already been mentioned, osteoarthritis and rheumatoid arthritis. They comprise the vast majority of cases that lead to joint replacements. Osteoarthritis is a chronic disease affecting multiple joints. It is characterized by thickening of the joint linings, and softening of the bones underneath the joint surfaces. It is strongly associated with aging and is progressive. On the other hand, rheumatoid arthritis is an inflammatory disease of the connective tissues, especially those of the muscles and joints. The inflammation usually strikes the joint linings also, with joint deformation occurring later in the disease. Rheumatoid arthritis usually waxes and wanes, causing increased damage and residual pain with each flare up.

Diseases of the blood may result in secondary problems for the joints. Two examples include: the bleeding disorder hemophilia and sickle cell disease. Hemophilia if severe enough, results in bleeding into the joint spaces, especially joints of the legs. Chronic intermittent bleeding of this kind can lead to progressive damage to the linings of the joint. In sickle cell disease, the small arteries and capillaries are blocked by abnormal red blood cells that characterize this disease. If the arteries which supply nutrition to the joints are blocked, damage due to tissue starvation can ensue.

In certain instances, trauma to the joint or to the immediate vicinity of a joint can cause degeneration of the joint in later years. Especially vulnerable is the head of the femur which has only one artery to supply it with blood. Fractures of the femur bone that severe that artery will lead to the death of the head of the femur. In other cases, especially in older people, fractured bone may not heal. If the fracture is adjacent to or within the knee or hip joint, loss of joint function becomes a distinct possibility.

Finally, the joints of the human body can become infected. If treated improperly or if undetected for a long period of time, infection can virtually obliterate the joint. If these infections can be eradicated completely, affected individuals could become eligible for replacement of the destroyed joint.

Another set of circumstances includes those patients with previous surgery of the hip or knee. Operations of the knee or hip can include a continuum from resurfacing on one side of the joint, to replacement, to fusion of the bony ends of the joint. If these repairs have failed, patients may become candidates for total joint replacement. And, if surgically possible patients who have had a total joint replacement fail, can have yet another replacement joint implanted (84).

Not all patients are eligible for joint replacement, even though they have severe joint pain and joint destruction. An active infection within the joint or anywhere else in the body is a firm contraindication for joint surgery. It is very difficult to eradicate such infections within a newly implanted joint, even with many modern antibiotics. In some cases, the only avenue for eradication of the infection is removal of the newly placed artificial joint. Therefore, most surgeons will treat the infections completely prior to undertaking surgery. A number of diseases inhibit the growth of new bone or promote destruction of existing bone. Since a joint prosthesis is imbedded in bone and is dependent on that bone for successful function and long-term stability such diseases are contraindications for joint implantation.

A small number of people have allergies to metals. On rare occasions they may react badly to the implantation of metal such as a joint replacement. Some surgeons feel that a strong past history of this kind of allergy is a contraindication for joint replacement surgery. Finally, any general medical condition which would prevent a person from undergoing nonemergency surgery, automatically eliminates them as a candidate for the surgery of joint implantation.

In addition to a person's state of health, the qualities which make each person different are carefully evaluated by orthopaedic surgeons. There are several critical factors to be considered: the level of activity engaged by potential recipients, age and weight, and patient motivation. Activity level and age can often be closely related. Most of the diseases previously described afflict members of society in older age groups (greater than age 50) (44). Generally, it is expected that older people will be less active than younger ones. To be certain, surgeons will probe extensively into patient's lifestyles to understand the kinds of physical activities patients would undertake if their painful joints were treated with replacements. The best results with joint implants can be expected in people who do not exert themselves excessively, and who are not expected to out-live the replacement joint (69).

In contrast, younger persons might attempt to resume vigorous lifestyles even with a new joint and so would be less likely to receive one. The treating physician would be concerned with the more severe stresses placed on the implant, and the possibility that the joint would dysfunction long before the patient would no longer need the device. Therefore, as a general rule, younger, more active patients will not be offered knee or hip replacements (57). Instead, other lesser surgery is offered to reduce pain until these patients are old enough to use, not abuse, the prosthesis. The approach is similar for overweight patients. Heavier patients place greater stresses on the implant; therefore, most surgeons direct overweight patients to reduce their weight. However, surgeons will rarely turn patients away from artificial joints for this reason alone.

The motivation of the patient is important in rehabilitation after surgery. While evaluating prospective recipients, surgeons will assess the patient's understanding of the limitations of the new joint, as well as, the effort necessary to gain maximum benefit from the surgery. People long immobilized because of joint pain need retraining of weak muscles. Not only are exercises prescribed, but patients need to regain confidence in their ability to go about many activities made difficult by the painful joint (45).

Chapter 7

Complications Associated with Joint Implantation

7. COMPLICATIONS ASSOCIATED WITH JOINT IMPLANTATION

Because every medical procedure carries an element of risk, it is important to identify the more common medical complications of joint implantation. Some of those complications have led to concerted efforts to reduce the problem .

The complications of knee implantation have been alluded to in the previous section on design evolution. The more important ones are: deep wound infection, (either during surgery, or after), dislocations of the joint, pain, and loosening of an implanted part from the cement and underlying bone.

Infections

Infections have always been a grave concern to all surgeons, particularly when the surgery is within a joint. The reason lies in the anatomical pecularities of the human joint. In contrast to many other sites in the body, joints have a particularly sparse bloodsupply. The amount of blood that flows into the tissues around the hip or knee joint is a small fraction of the blood flowing into an equivalent area of skin or muscle. Antibiotic therapy depends on the blood stream to bring the medicine to the area of infection. Therefore, antibiotics arrive to a joint in amounts directly proportional to the bloodflow. Often, insufficient amounts of such drugs are delivered to the joint to be effective in fighting infections. Bacteria combined with a foreign body (whether metal or plastic) as can occur with a joint implant can result in an infection that is difficult to cure. In general, infections at the site of foreign bodies will persist, despite treatment, until the foreign materials are removed. Thus, great care is necessary within the operating room at the time of surgery (69,84).

Infection rates tend to be proportional to several aspects of surgical procedure such as: the amount of time an open joint is exposed during operation, the amount of foreign material implanted into a joint, and the shedding of infectious agents by the surgical team working at the operative site as well as those in the immediate vicinity of the operational field who help the surgical team. The thrust of sterile techniques and procedures within the operating room (OR) is directed at the latter factors. Even the best surgeons can only work so quickly, and there is a minimum of material which must be implanted if a functioning joint, able to withstand the stresses placed on it, is to result. Since the beginning of the joint implantation era, a great deal of controversy has been generated over the methods needed to insure adequately sterile environments in the OR.

In the early 1960's, Charnley reported an infection rate for his total hip replacement cases of approximately 6.6 percent (17). This high infection rate prompted him to introduce a variety of techniques into his OR in an attempt to reduce it. Charnley reported his results in a series of papers and at conferences, and his extensive findings launched the controversy that persists today (14,16,17). A criticism brought against his work referred to his simultaneous introduction of several different sterile techniques. This made it difficult to correlate changes in the operative infection rate with the particular method(s) introduced. Furthermore, tests to determine the level of bacteria in the OR, some of which he employed in his studies have been controversial as well (16). As hip replacement surgery began to take hold in this country, infection rates experienced here were found to parallel those reported by Charnley (84).

A variety of methods has been available to reduce bacterial contamination in the OR. Traditional systems exchanged the air in the OR: filtering, controlling temperature and humidity, and moving the air from the inside to the outside. The air in a standard OR is completely replenished once every 6 minutes. Other traditional techniques include: reducing the number of ancillary personnel in the OR, using head covers and a nose-mouth mask, and excluding from the OR those with active infections (51).

Newer methods of reducing bacterial contamination center on two themes. One reduces the amount of bacterial shedding from operating personnel, and the other reduces the level of airborne bacteria in the OR. To accomplish the former, double surgical gloves have been used, as well as double masks. In more recent years, air-conditioned sterile suits similar to "spacesuits" have been brought into the OR. These suits isolate the head and upper torso from the operative field. Air is exhausted from the head down to the feet and them out the room. In order to better cleanse OR air, equipment is available that increases the rate of air exchange. Furthermore, the air is passed through elaborate filtering systems designed to remove particulate matter upon which bacteria harbor. This air is moved in a systematic way around the room (laminar flow) so that it never recirculates over the operative area (14,51).

A persistent question has been: Which of the many available systems are the best? Which provide the best results for the least cost? In 1974, the Governing Board of the National Academy of Sciences (NAS) approved a project to investigate this problem and report its findings. A committee headed by Dr. G.T. Aitkens under the auspices of the American Academy of Orthopaedic Surgeons had originally solicited the NAS for help in investigating the problem. The Workshop on Control of Operating Room Airborne Bacteria met in November 1974 to consider the problem and possible solutions. The report is over 300 pages and will not be reviewed. Agreement on specific recommendations was reached by the 40 participants at the workshop concerning recommendations for future research (51).

Today, infection rates for knee and hip surgery hover between 1 and 3 percent. The controversy still persists and research continues. Even though this research is not directly related to the technology of joint implants, it is joint implantation that has generated the need for improved sterile techniques.

Loosening

Loosening is the progressive loss of attachment between bone, cement, and the implanted device. Evidence of loosening can be detected on X-rays for it appears as dark lines around the perimeter of the device. As these lines become prominent, they indicate there is little or no contact between the device, the cement, and the bone. A predictable relationship does not always exist between the X-ray evidence and the clinical symptoms of loosening. Patients can function for many years after evidence of loosening has appeared on the X-ray, while some others cannot (10). A prominent symptom is pain, caused by the loose device shifting around in the bone. The pain is more evident during activities than when at rest. If enough stress and load is placed on the loose implant it will break and the patient may often hear and/or feel the snap.

One of the most significant features of the Charnley total hip replacement was the introduction of cement (13,84). In 582 cases reported by Charnley from November 1962 to December, 1965, only 1.0 percent had loosening of the cemented implant (15). Results such as these catapulated joint replacement into prominence. Loosening data on total hip surgery has become the yardstick by which other types of joint replacements are measured (69). Late implant failure due to loosening of the hip and knee prosthesis has become more and more evident.

There are several choices available to a surgeon when confronted with a patient who has a loose implant. The therapy chosen will depend on the condition of the bones and tissues around the joint, as well as the overall medical condition of the patient. If little or no damage to the tissues of the joint has occurred, and if the bone is in good condition, a surgeon can revise the joint. The ability to do such revisions, though, decreases proportionately to the amount of bony damage around the loose implant (23,84). In more complex cases, custom implants are often designed by the treating physician in conjunction with a manufacturer. In the typical example, a standard implant is altered to make it suitable for use in a patient with the problem. The manufacturer will then custom-make the implant especially for that person (3,31). There are instances, however, when revision surgery is not possible. The only alternative at that time is performing a bony fusion of the joint. The resulting solid joint area is painfree and stable, but is incapable of any motion (9,69).

The anticipated rise in the failure rate for older replacement joints has stimulated a research effort devoted to finding better ways of attaching the implant to bone.

Dislocation

Good knee function after replacement is dependent on adequate range of motion, and stability of the joint throughout the entire range, so that a person can perform life's daily activities. A distinction among knee models available today is the degree of constraint built into them. The less natural stability a person's knee has, the more constraint the prosthesis must provide if adequate function is to result (9,69).

An important task for orthopaedic surgeons is the evaluation of patients' knees in order to determine the amount of inherent natural stability remaining and the degree of joint deformity present. Then they select a knee prothesis that will compensate for the knee deficiencies found. Surgeons must be able to comfortably use a number of different prostheses in the OR, in order to provide the patient with the correct type of device. Emphasis is repeatedly placed on the importance of careful and meticulous surgical technique, in order to gain good outcomes. Attention to the many details of patient evaluation, device selection, and surgical technique ultimately allows patients to perform to the best of their ability (69).

Postoperatively, knee instability or dislocation can be traced to several reasons. Incorrect matching of a patient's knee to a prosthesis is probably a common cause. Poor surgical techniques in preparing the knee for implantation or in the alignment of the device occur but are very difficult to document. Postoperative care which disrupts the knee before adequate healing has taken place can be devstating. The frequency of joint dislocation is not always reported in articles on knee replacements. The studies that do mention it note that patients were incorrectly evaluated, rehabilitated improperly, or suffered damage to the knee after surgery.

As mentioned earlier, knee instability was more commonly experienced with the early knee designs but only during certain types of activities, such as going downstairs, patients with instability have been studied in the laboratory for the purpose of improving those designs (9).

There are other complications of knee and hip implantation which are important but not common. Some are a function of the surgical procedure itself, such as superfiscial wound infections, lung disturbances after surgery, and temporary nerve dysfunction. The overall complication rate for hip and knee surgery has decreased since 1960. Better operating room conditions, improved surgical techniques and the accumulation of experience with these devices has contributed to the improved results obtainable with artifical joint replacement (69).

Chapter 8
The Rehabilitation of Joint Recipients

8. THE REHABILITATION OF JOINT RECIPIENTS

Besides eliminating the pain of arthritis, joint replacements make a significant improvement in the functioning of patients. This can release many debilitated or handicapped people from other supportive services. The rehabilitation of such recipients is often dramatic enough to make them self-sufficient in many ways. Rehabilitation technology and expertise is usually needed after surgery to get maximum benefit from the newly placed joint.

Once surgery has been successfully completed, and patients are convalescing, it is important to familiarize them with their newly functioning joints. In larger hospital centers, this task falls on a 'rehabilitation team' composed of orthopaedic surgeons, psychiatrists, physical therapists, and activity therapists. In smaller hospitals, the rehabilitation of the patients may fall to physician therapists in conjunction with orthopaedics, or to the nursing staff. These 'teams' collectively evaluate patients preoperatively, and help recipients prepare for surgery and the rehabilitation program that follows. The amount of time devoted by such teams to typical recipients is relatively smaller than the time spent to rehabilitate other chronically disabled people.

Typical recipients are usually very excited at the prospect of having a pain-free joint that will enable them to walk again. This eases many of the rehabilitative burdens typically encountered with the chronically handicapped. In typical cases, patients may be seen the day after surgery by a therapist and begin exercises for the leg and the operated joint. During the first week, the patient's joint is slowly stretched and strengthened. Many recipients have not used the diseased joint in some time because of the pain. This inactivity quickly causes the surrounding muscles to weaken. Motion around the repaired joint is slowly increased to stimulate the circulation and to prevent stiffening of the tissues. Within 10 to 14 days, these patients are on their feet walking with the aid of a 'walker.' Of course, the patients experience pain after surgery, but they often report that the surgical pain is only a 'tweak' compared to the excruciating pain in their previously arthritic joint.

As the postoperative pain subsides and the tissues around the surgical wound heal, patients place more weight on their legs and joints, systematically strengthening their muscles. Activity therapists reacquaint them with many long abandoned activites. They get practice walking on level surfaces, are introduced to stairs again, and are taught other activities associated with daily living. Throughout the process, the therapists and surgeons are helping patients rebuild confidence in themselves and their legs. Within 21 to 28 days recipients are ready to return home to continue exercises and practice drills. After 6 to 9 months, most have fairly good levels of functioning, the extent of which depends on the patient's physicial and medical condition, as well as their motivation to gain maximum benefits from the joint.

Anyone who has seen patients walk after crippling arthritis of the hip will be astounded at the completeness of the recovery. In many instances the patients can go back to work if they desire and if they have no other limiting conditions. For those who do not get maximal function, the relief from pain and a lesser degree of functioning can be very satisfying as well.

Chapter 9

Factors Contributing to the Diffusion of Joint Implants in the United States

9. FACTORS CONTRIBUTING TO THE DIFFUSION OF JOINT IMPLANTS IN THE UNITED STATES

The actual diffusion of joint implants in the United States is almost impossible to trace. Such a determination requires records of the availability of implants in every region of the country from the early 1960's on. Such records are difficult to obtain and apparently there has been no attempt by others to assess and quantify this area. The upcoming section discusses those factors which have contributed to or have influenced the diffusion of these devices.

The diffusion of implant equipment, surgical techniques, and principles of design parallel the general pattern governing diffusion of information in medicine. Introduction of the Charnley hip replacement can be found in a small three page article published in Lancet, a British medical journal (13). In 1966, widespread attention to focused on Charnley's breakthroughs at the Society of International Orthopaedics and Trauma Surgery, when he presented the first large series of results of his hip operations (84). The presentation generated great excitement. Orthopaedists attending the conference returned home hoping that a new era in joint replacement had finally arrived. Soon after, many surgeons began visiting Charnley in England in order to learn about the device and the surgical techniques for its use. American orthopaedists also participated in such excursions to England, returning home with the necessary devices, instruments, and cement (84). They soon began implanting very limited numbers of such hips into eligible patients. By 1969, the American orthopaedic community was eager to make the Charnley hip widely available. Howmedica Inc. was interested in meeting that need, and began preparations for its introduction. However, it felt obligated to supply all the technology necessary for implantation, including polymenthyl methacylate (PMMA). The Food and Drug Administration (FDA) interceded and held up the release of PMMA for general use in this country (84).

Until the mid-1960's the FDA had been cautious about exercising its power over medical devices. By 1969 though, the FDA had the clear authority to intervene prior to the release of medical devices (4). In an attempt to intercept the generalized use of joint implants, FDA rule that PMMA was a drug subject to premarket approval. The ruling prevented the widespread use of implants until 1971. In the intervening 2-year interim, the FDA accumulated data generated in various medical centers on the safety and effectiveness of PMMA. An organization instrumented in the effort to gather this data for use by FDA was the American Academy of Orthopaedic Surgeons (AAOS) (84). It helped locate and coordinate researchers across the country for PMMA trials. Under pressure from the orthopaedic community, the FDA released PMMA in 1971 for use in the total replacement for hips (21,84).

In anticipation of the upcoming boom in total hip replacements the AAOS carried out its primary charge: to provide continuing education for practicing orthopaedists and to provide a forum for the presentation of scientific work in the various fields within orthopaedics. The AAOS spearheaded efforts to educate surgeons in the techniques necessary for hip replacements and in the accompanying medical indications and contraindications for its use. Workshops were organized regionally around the country on the surgical approaches for hip replacement and cementing techniques. The instructors for the courses were generally the surgeons who had visited

Charnley in England. The AAOS continues to remain active in similar areas. It identifies needs in the orthopaedist's education, tries to fill those, needs, and has drawn attention to areas of orthopaedics which need research and investigation (84).

Continuing education courses are critical to the many practicing orthopaedists who wish to stay up-to-date. Courses are offered by individual medical centers, medical societies, medical schools, and the AAOS. Continuing education was instrumental in quickly training many surgeons in the rudiments of hip replacement. However, the best way for surgeons to gain experience has been to spend time in the operating rooms and clinics with well-experienced practitioners. This practice also accounts for the diffusion of surgical expertise on implantation (84).

Today, aspects of joint implant technology are taught in all levels of medical education starting in medical schools and continuing on through residencies. Medical education is likened to an apprenticeship; experience in joint implantation comes from contact with patients in the clinics and the operating room. The trend in orthopaedics recently has been to extend residency training from 3 to 4 years in order to provide sufficient time for adequate experience. The extra time is devoted to pursuits such as basic science research or clinical investigations, as well as to an increase in the time residents are trained under supervision in the operating rooms and clinics. Besides learning the details of existing prostheses, the better residency programs also teach residents how to evaluate new prostheses as they appear in future years, a skill that is very important in this rapidly changing technology (26).

The manufacturers of implants have played a fundamental role in the diffusion of implant technology. One strong influence has been the plethora of implant devices available to the orthopaedist for the hip and knee. The implant manufacturers actively introduced any design variation in these joints that held hope for improved results and, therefore, increased sales. Many manufacturers waited for ideas to flow in from the field, which they analysed and often tried, if feasible (3,31). As noted, over 80 such designs were available by 1973. Often, manufacturers make minor variations in a device to suit the needs of a particular surgeon. However, if that surgeon is influential in his region or area, they can assured that demand will increase from other surgeons in the same area. Not only are practicing physicians influenced, but residents-in-training are influenced by local custom design alternations as well. As a service to the wide variety of surgeons in the U.S., some firms, such as Zimmer-USA, offers devices for sale that have not been used in many years. These practices allow treating physicians enormous flexibility in the choice of the device to be used in a patient (31).

The orthopaedic device industry conducts much of its business in a similar fashion to the drug industry. The sale representatives for the device firms are essential to the success of the firm, its products, and to the surgeons. The sales representative is a primary source of new information about new device technology. They provide basic information on: a device, its intended uses, and articles written by others about the device. The manufacturers will provide their sales repsentatives with brochures, audio-visual materials, video-cassette presentations, as well as samples. The smaller firms cannot afford to provide the same variety of advertising and demonstration materials as can the larger ones. On occasions, the larger manufacturers will sponsor seminars on prostheses, usually taught by the devices' originators. More likely though, manufacturers will donate equipment and supplies to training seminars sponsored by other groups (8,2[illegible],32).

Each individual firm will stress different features of its product line. For example, Biomet Inc. will draw attention to its expertise in fabricating Titanium implants and the positive features of Titanium for use as an implant material (30). On the other hand, a large firm, such as Zimmer-USA, stresses it large selection of high-quality devices. Of the U.S. manufacturers, Zimmer-USA claims to have the most stringent quality-control standards, a point it does not hesitate to emphasize to customers (38). In recent years the firms have commissioned laboratory studies on the biomechanical properties of their products to demonstrate superiority over competing brands (3,31,30). Only in the past several months, However, have these firms begun to consider financing the clinical trials necessary to show the virtues and faults of their implant products, a phenomenon that can be traced to the Medical Devices Act (3,31).

The major event of the year for both the academic and the general orthopaedic community, as well as the manufacturers, is the annual AAOS convention. This convention is the meeting ground for all the orthopaedic societies (Hip Society, the Orthopaedics Research Society, etc) and as such facilitates the exchange of current information. In addition to those meetings, the manufacturers set up exhibition booths filled with their wares. The exhibit floor serves several functions, the most obvious one is to sell products. The presence of those products allows participating surgeons to see devices discussed at meetings. It is not uncommon for a prominent surgeon to stroll along the exhibit floors. Informal discussions between such people and other surgeons quickly become impromptu lectures on devices, instrumentation, and procedures (57).

One of the few places to get current data on implant technologies and the results of their use is in a meeting such as the annual AAOS convention. The underlying reason for this is that medical literature is usually at least six months behind current developments. Journals such as the Journal for Bone and Joint Surgery can lag behind by as much as three years. The AAOS meeting in 1978 attracted 3,554 orthopaedics and many interested guests, totaling well over 30 percent of the practicing orthopaedists in the country (11).

Chapter 10

Federal Agencies and Their Policies Toward Artificial Joint Replacement Technology

10. FEDERAL AGENCIES AND THEIR POLICIES TOWARD ARTIFICIAL JOINT REPLACEMENT TECHNOLOGY

The current attitudes and policies of the Federal Government are identified and reviewed in this chapter. Analysis on the impact of those policies will be discussed in Chapter 12.

The Government participates and influences many stages of joint implant technology. Basic science research is supported by the National Institutes of Health (NIH), and the Veterans Administration (VA). Applied science research is often financed by grants from the National Institute of Handicapped Research (NIHR), the National Aeronautics and Space Administration, as well as the NIH and VA. Clinical trials and the establishment of safety and efficacy has been one area where Government has played a predominantly regulatory role. The evaluation of such trials and the protection of our society from harmful or dangerous devices is the responsibility of the Food and Drug Administration (FDA). The use of joint replacements by surgeons, all over the country, is to a large extent governed by policies set by third-party payers, such as Medicare and private insurers.

The National Aeronautics and Space Administration (NASA)

The role of NASA in supporting research and development is unusual. As a so-called 'high-technology' agency, its charter mission includes a mandate to apply its technical expertise to areas outside aeronautics and aviation wherever possible (75). NASA usually transfers this knowledge to other scientific fields fields with assistance from other arms of the executive branch. NASA's Office of Technology Transfer (OTT) is responsible for these activities.

Over the past 7 years, NASA has been involved in several ventures that relate to joint implant technology. Bioengineers have dreamed of 'getting inside' the joints in order to directly measure the stresses and loads encountered during different levels of activity. In a sense, NASA had been doing just that through the telemetry systems it has used to explore other planets. The Jet Propulsion Laboratory of the California Institute of Technology (JPL) has been a prime developer of telemetry systems (56). In 1976, a bioengineer at the University of California at Los Angeles (UCLA) familiar with JPL's expertise, approached NASA and JPL with a project to develop an implantable hip telemetry system for use in humans (48).

The feasibility of such a project was first investigated by JPL using its own funds. JPL determined that it had the ability to design and construct the necessary electonics and hardware for placement of a system inside the head of an artificial femur component. Such a device and its electronics would then be implanted and used normally by the recipient. When desired, information could be transmitted from within the femur head to equipment outside the body (48, 56).

The project was further validated by NASA-OTT before funds were committed. A scientific literature search and a survey of prominent bioengineers was undertaken to verify the usefulness of such a device and the data it could produce. A conference was also arranged in coordination with the Rehabilitation Services Administration (RSA-NIHR) between JPL, UCLA, and staff from the Rehabilitation Engineering Institute at Northwestern University in Chicago (see section on RSA-NIHR). OTT concluded that such a telemetry system would be different from two other systems being designed independently at Case-Western Reserve University in Cleveland and the Massachussetts Institute of Technology in Boston. NASA allotted $400,000 for a three-year program to develop prototypes of the system (75).

The Office of Technology Transfer surveyed other Federal agencies for funding support and to determine the level of interest in such a telemetry system. NASA's methodology does not always completely mesh with the proposal evaluation systems in use by other agencies. In particular, the peer review systems, often employed by other Federal agencies for evaluating scientific projects, take months to approve action on a proposal. NASA, ready to fund this project, was not prepared for the long wait (32, 75). Ultimately, the RSA provided a one-year grant of $70,000 for this project (61). In 1977, the work to develop an implantable hip telemetry system began in earnest, and the hip prototypes were completed in late 1979. NASA incurred all the costs of applying its technology to the hip implant. UCLA provided the medical knowledge and related funds to make the hip implants useful to its potential recipients. As completion of the prototypes neared, UCLA organized and submitted a project proposal to the National Institute on Arthritis, Metabolic and Digestive Diseases (NIAMDD) for consideration by the Orthopaedic Section. It requested funding of the project in the laboratory pretesting phases, prior to human implantation. NASA was to take a supportive posture, lending technical assistance when necessary. Since 1980, when the proposal was submitted, NIAMDD has denied funds on several occasions, the most recent being March, 1981. At present, the proposal is being considered for funding by the Veterans Administration (48).

Another project supported by NASA also originated from JPL and UCLA's orthopaedic department. The concern with implant loosening has generated interest in finding alternative methods of attaching devices within bone. One such avenue of investigation involves materials which potentially encourage bone to grow into and around the implant thus 'locking' it into place. JPL and NASA have an expertise in many ceramic materials which are porous and could be applicable to such an endeavor. Therefore, NASA funded a study to explore the feasibility of using such ceramics on joint implants. Problems soon appeared that were biological in nature. The bone was not growing adequately into the ceramics being used. Before the project could continue, information about this biological phenomenon had to be collected. NASA's interest only encompasses the application of the ceramics technology to joint implants. It has had no desire to fund the basic biological research needed to understand the growth of bone in ceramics; therefore, NASA terminated funding after one year (75).

Recently, NASA contracted a study on the application of aerospace technology for the improvement of surgical implants, specifically in the area of metallurgy. The study is currently underway under contract NAS16567 and the study contractor is Eagle Engineering of Texas.

At the time of this writing, NASA is not actively engaged in any other projects concerning joint implant technology or closely related areas. Furthermore, NASA is not currently engaged in preliminary inquiries with regard to future projects.

National Institutes Of Health (NIH)

One of the principle sources of Government research funds in medicine has been the NIH. Since its creation, the NIH has given a low priority to funding investigations in the area of orthopaedic joint implants, as well as all of Orthopaedics in general (26,32,53). In the 1960's, projects related to joint implant research were considered by a General Surgery Section with little input from orthopaedists. By 1970, such project proposals were channeled to the Applied Physiology Section, more able to review orthopaedic projects including implants, but still only involving several orthopaedic surgeons in the review. In 1976, the NIH formed a separate Orthopaedic Panel with a peer review committee composed solely of researchers committed to orthopaedics and related investigative efforts. The Orthopaedic Panel is a part of the Musculo-Skeletal study section of the NIAMDD (32, 26).

Many active areas of basic science research, alluded to in other sections of this report, are supported by NIAMDD. However, clinical trials of prostheses are not generally funded. It is the view of NIAMDD that there is sufficient incentive to fund clinical trials in the private sector. These trials are closely linked with the marketability of a device and NIAMDD sees a strong motive on the part of industry and the medical community to fund such endeavors. This aside, NIAMDD conceeds that it cannot easily afford to fund clinical trials of prostheses because such trials take many years to complete (often 50 years or more) and the NIAMDD would be required to set aside significant sums of money over those years to assure that the study would be completed (32).

The budget priorities of the NIH are under the overall control of the Congress which mandates, in a broad sense, national medical research priorities (32). The low level of funding for all orthopaedics simply reflects those priorities. For fiscal year 1981, the NIAMDD allocated approximately 286.8 million dollars for funding research projects. Of that, 1.6 million dollars was allocated to the Musculo-Skeletal Section, or 0.56 of the NIAMMD budget for research. NIAMDD recognizes that the level of funding for orthopaedics is not well-correlated with the level of expenditure in the health system for orthopaedic care (32).

A very interesting project to be undertaken by NIAMDD in the upcoming year is a Hip Consensus Conference and Report. Such Consensus Development Conferences have been held by NIH in many other medical areas, such as Coronary-Artery Bypass Surgery and Caesarian Childbirth in the U.S. The purpose of such conferences is to synthesize available knowledge and highlight questions that need clarification and discussion. The panelists review the literature and solicit state-of-the-art reports on current fields of investigation which could affect the discussion of the questions. The panel reads all the material provided and meets to arrive at a consensus statement. Dr. P.D. Wilson, Jr. is Panel Chairman on the upcoming Hip Consensus Conference. Questions on the hip implants are not yet available, but the probable issues will include loosening, device life-span, surgical indications, etc. (32,84).

It is the general impression of many inside and outside of the NIAMDD that the support for orthopaedics and related research is slowly increasing.

However, there is little anticipation that orthopaedics will be designated a 'critical-need' research area in the near future. The U.S. Congress and the NIH apparently do not perceive the diseases treated in the orthopaedic realm as a pressing national research priority.

National Institute Of Handicapped Research (NIHR)

The NIHR (formerly of the Rehabilitation Services Administration), has been mandated to fund research in various fields of rehabilitation that clearly leads to benefits for patients (70). Of three university research centers it directly funds, one is devoted in large part to joint implantation. The Northwestern Rehabilitation and Engineering Institute in Chicago serves the population, over 400,000 people, of Cook County, Illinois. It is directed by Drs. Lewis and Childress, both bioengineers. Of $35 million in the NIHR budget for fiscal year 1981, NIHR allocates approximately $8 million to rehabilitation engineering projects. The group at Northwestern receives approximately 10 percent of that (55, 70).

Of the more than 30 ongoing projects, 14 are devoted to joint implant or directly related research. Investigations are taking place in device wear analysis, stress and load analysis, new implant designs, and biological and bioengineering projects on the interface between devices, cement, and bone. Other projects include basic research on new materials with possible joint implant potential (55).

The is unique in its flexibility when approaching and conducting investigations. Data collected in a basic science area can be applied to a practical problem often by the same researchers. This allows continuity from basic to applied science endeavors for the staff at Northwestern, not always available in other laboratory settings (18). In recent years, Northwestern has released a tribial component in conjunction with Howmedica Inc., for which Northwestern receives royalties. In the past, Biomet Inc. has also been involved in development projects with Northwestern. The group at Northwestern also publishes its finding in many areas, as well as presenting information at conferences and meetings (18, 55).

Because NIHR's policy is to fund projects with direct application of data to patient care, it has tended to avoid funding projects which are designed solely for knowledge's sake (61,70). A case in point is the JPL-UCLA project on hip telemetry described in detail in the section on NASA. The project was funded by NIHR (then RSA) in anticipation of direct gains in hip implant research and technology in the near future. However, the pace of developing the telemetry system and the time lag before usable data would be available, led NIHR to withdraw support until the system is further developed (61).

At present, besides ongoing research at Northwestern University, NIHR is not actively considering or funding projects in joint implant technology or related research.

Veterans Administration (VA)

The mandate of the VA is well known to most people. It cares for the veterans of war with priority given to those injured in the line of duty. Improvements in medical care in the 1930's and 1940's were responsible for saving the lives of many men in combat who would have otherwise died. In many instances, they returned to the U.S. in desperate need of rehabilitation. The close of World War II brought rehabilitation medicine within the VA system. The Rehabilitation Engineering Research and Development section (RER&D) was organized in 1948 with a $1.0 million budget to fund research in this area (50). It was not until the early 1960's, however, that the RER&D section began to take notice of artificial joint implantation. To some extent, this can be traced to the activities of early orthopaedic surgeons in bioengineering, such as Dr. V. Frankel, who served on the National Research Council in the early 1960's. He and others promoted bioengineering and joint implant technology to the RER&D section hoping to expand its interests and horizons (26). Over the ensuing 15 years, RER&D slowly began to gain such interest.

The impetus at the VA for earnestly undertaking joint implant projects came from Dr. V. Nickel, director of RER&D from 1977 to 1980, the first orthopaedist to hold this position. During his tenure, he actively encouraged the orthopaedic community to participate in VA research activities. The poor support given orthopaedists by the VA in the past caused many orthopaedists to seek research facilities and funds outside the VA system. Testimony to this fact can be seen in the orthopaedic services at major VA Medical Centers which are not nearly as elaborate as their sister Rehabilitation Services. Under Dr. Nickel's guidance a newly formed peer review system with RER&D was created, and over the past three years a steady increase in the number of funded orthopaedic projects has occurred (19, 26, 50, 53).

The VA is currently funding 7 projects related to implant technology: 3 are centered on improving cementing techniques, 1 is on loosening, 1 is on analyzing the stresses and loads on the hip joint, and another is being conducted on the nature and effect of particles that wear off of implants. These 6 projects were allocated $212,500 in fiscal year 1980. The seventh project funded by the VA is on implant retrieval analysis at the Department of Bioengineering at Tulane University. This project has received funds from the VA since 1977. The Tulane Project has been one of the most prominent in the country. Its director has organized conferences on Retrieval Analysis under the auspcies of several Government agencies such as the National Bureau of Standards, the VA, and the FDA (82). This project was budgeted $80,000 for fiscal year 1980. In all, RER&D devotes over 10 percent of its budget to implant technology and related research, or almost $300,000 (19).

Besides funding research in rehabilitative and implant technology, the RER&D section publishes its own journal, the Bulletin of Prosthetic Research. The journal accepts articles for publication on VA-sponsored research and is available both inside and outside the government (50).

In the future, the VA may fund a prospective multi-center clinical trial on joint implants. The VA is a good setting for such a trial, performing over 5,000 total joint replacements per year (47). The impact of such a study could be extensive within the VA, since it is a volume buyer of such implants, as well as on the medical community at large. However, at the present time, no clinical trial is being planned (36).

In contrast to many other technologies directed towards the treatment or care of the handicapped, the issue of reimbursement in implant technology is not as controversial (60). The average age for an implant recipient is the middle to early 60's. It can be assumed that many of those people are covered to a large extent by the provisions of Medicare. The Health Care Financing Administration (HCFA) administers and maintains records of all reimbursement activities under the Medicare provisions. An attempt to learn the date of the first reimbursements for artificial hip replacement proved unsuccessful. In the mid-1960's when HCFA was formed, and when joint replacement began in the United States, the International Classification of Diseases (ICD) was in its eight edition. The ICD-8 did not make a distinction between total hip replacement (the femoral head and acetabular cup) and other forms of hip repair available, such as cup arthroplasty. Therefore, a review of HCFA records, which used ICD-8, could not reveal when Medicare began reimbursing for this particular operation (7, 60).

HCFA has paid for total joint replacements since the 1960's, regardless of the device used and its popularity or disrepute. If a surgeon wished to use a joint replacement out dated by ten years, HCFA would reimburse the device and the procedure. Over the years after total joint replacement was introduced, HCFA has not undertaken an analysis of its reimbursement policies towards joint replacement. It has, reportedly, uniformly and consistently paid all claims (60). Surgeons strongly feel that device selection is a central part of treatment and cannot be determined as a matter of policy. HCFA has concurred (7). At present, there are no plans underway at HCFA to establish payment policies in this area. It is well-known that clinical studies on joint implants conducted over the years have often been indirectly paid in part by Medicare, as well as other third-party payers such as Blue Cross & Blue Shield (BC/BS), in the form of reimbursements for the hospitalization, procedures, and devices used in such studies (26, 60).

Similar statements made about HCFA can also be applied to BC/BS. The nature of the ICD-8 classification prevents collection of statistical and historical determinations of total hip replacements in the mid-1960's. The Blue Cross regional plan for the State of California shows that Blue Cross first reimbursed for a total hip replacement in March 1972. Similarly, reimbursement for knee replacements began in July 1972 (64). These dates probably reflect improvements in classifications of total joint operations, rather than the true history for reimbursements of joint implants in California.

With regard to reimbursement policies, BC/BS also pays all claims for joint replacement. It, too, does not anticipate a policy review of such payments in the near future (64).

Food And Drug Administration (FDA)

The medical devices industry has recently been placed under the scrutiny of the FDA. The Medical Devices Amendments to the Food, Drug, and Cosmetic Act was passed in May 1976. The provisions of that law placed all medical devices under the similar controls to those exercised over drugs. This act has had a more profound effect on joint implant technology than any other single Federal action (E). Therefore, it is important to examine the Amendments and their impact both for the present and the future.

Concern over the proliferation of medical technology can be traced as far back as the Kennedy administration (40). In 1962, overwhelmed by the thalidomide tragedy, the U.S. Congress amended the Food, Drug and Cosmetic Act by requiring that drugs be proven not only safe, but also effective prior to commercialization and sale. In considering the 1962 Amendments, medical devices were not specifically included. The technological boom in medicine continued in full swing, and many people both in and out of Government realized that medical devices would eventually follow.

In 1969, the Department of Health, Education, and Welfare (HEW) formed a study group on medical devices, chaired by Dr. T. Cooper, then director of NIH-National Heart and Lung Institute, and an Assistant Secretary of Health at HEW. The "Cooper Committee" spent six years studying problems with devices, and many of its recommendations can be found in the Amendments of 1976. Actual work on the bill began in 1972, but it was not until 1976 that the bill finally passed. As noted by a Congressional observer, there was no sensational tragedy to spur action of this bill (4,40).

In the mid-60's, device manufacturers and members of the orthopaedic community began to organize information about the many different kinds of orthopaedic implants (besides joints) in anticipation of a Federal regulatory law. The AAOS organized a group of orthopaedists, bioengineers, and manufacturers under the auspices of the American Society for Testing and Materials (ASTM) to standardize the materials and manufacturing practices used in the production of those products (2,26,84). At present those standards are used by the manufacturers for the production of all implants.

The Amendments of 1976

The Amendments created three categories of devices, as recommended by the "Cooper Committtee," thus recognizing the wide range and variety of devices used in medicine. These categories, listed below, reflect the potential harm the devices pose to users (F).

Class I devices are only subject to the 'general controls' long in use at the FDA. They include: device adulteration (such as sterility), misbranding, and misregistration. The FDA determines if these general controls are sufficient to assure device's safety and effectiveness. Class I devices cannot be used to support or sustain life, nor be of importance in preventing impairment to human health. A typical example would be a tongue depressor.

Class II devices cannot be judged safe and effective based on general controls alone. Therefore, the FDA can require that devices meet performance standards, if enough information exists to devise such standards. They can include: methods of construction, quality control provisions, device testing, and so on. General controls are also enforced for Class II devices. Currently, all artificial joints are in this category (except one).

Class III devices must be accompanied by assurances of safety and effectiveness beyond those offered in the Class II category. Devices must get pre market approval (PMA) prior to release. Applications for that approval must include information demonstrating in a scientifically acceptable manner that the device functions as intended in a safe and effective manner. Devices used to sustain or support life, that are implanted, or used to prevent impairment to human health, must be automatically placed in this category. Therefore, new joint implants introduced after May 1976 have been placed into this category.

The Act provides a unique method for classification of old and new devices not used in the regulation of drugs. Devices are organized according to medical and/or scientific field; therefore, there is a classification advisory panel for orthopaedic devices. Such panels are required by the Medical Device Act to recommend to the FDA a Class for every device on the market at the time of the Amendments enactment, as well as all future devices.

Joint implants introduced after May 1976 have been automatically placed in the Class III category, unless the manufacturers demonstrate such devices to be 'substantially equivalent' to pre-enactment devices in a lesser Class. If a joint implant can be proven to be 'substantially equivalent' to pre-enactment devices in a lesser class, the manufacturer may circumvent the PMA approval process and release the device. Manufacturers petition the FDA for such reclassification under the Act's 510(k) provisions. The Orthopaedic Advisory Panel has been asked by the FDA to help consider such applications on several occasions. The panel evaluates the data submitted in the 510(k) and makes its recommendation to the FDA. Final classification decisions, however, rests with the FDA.

The role of the device panels is very important because they classify all pre-enactment devices, and because they must consider and recommend action on all PMA's. Problems between members of the orthopaedic community and the FDA led to a nearly four-year delay in determining and implementing a classification scheme for orthopaedic implants including joints (see tab 4). Between 1976 and 1979, resignations from the Orthopaedic Advisory Panel were commonplace (21,49). Because the Medical Devices Act specifically requires panel input, the FDA was unable to make those device classifications. By the spring of 1980, the FDA in conjunction with the AAOS finally organized a stable panel which has functioned well until the present time (22). Classifications have been finalized, as recommended by the Panel, but fears remain that tensions between orthopaedists and the FDA will persist.

Over the past 5 year, the implant industry has made extensive use of the 510(k) provisions. It has become routine for the FDA to request increasing amounts of information on a device to be 'grandfathered' with a 510(k). In 1978, guidelines were issued on the kinds of information needed (22).

a) the device had to replace the same structures as pre-enactment devices,

b) the bioengineering characteristics of the device (its kinesiology) had to be similar to pre-enactment devices,

c) the materials used in its construction had to be similar,

d) the claims for the device, such as indications, had to be similar, and,

e) the devices' clinical reliability could not be significantly different from pre-enactment devices.

The FDA has repeatedly acknowledged that the last parameter (e) is the most important in determining the equivalence of a device. Manufacturers have argued that the requirement (e) is tantamount to requesting an abridged pre-market application because clinical results had to be provided. The kinds of

Table 4

Classification by Generic Term of Artificial Hip and Knee Joints

Semi-constrained hip prosthesis - metal cemented acetabular component.
Semi-constrained hip prosthesis - metal uncemented acetabular component.
Semi-constrained hip prosthesis - metal/composite.
Semi-constrained hip prosthesis - metal/polymer.

Semi-constrained patellofemoral (knee) prosthesis - polymer/metal.
Constrained patellofemorotibial (knee) prosthesis - polymer/metal/metal.
Semi-constrained patellofemorotibial (knee) prosthesis - polymer/metal/polymer.
Femoral (hemi-knee) prosthesis.
Patellar (hemi-knee) resurfacing prosthesis - uncemented.
Tibial (hemi-knee) resurfacing prosthesis - uncemented.

Constrained hip prosthesis - metal.
Constrained hip prosthesis - metal/polymer.
Femoral (hemi-hip) prosthesis - metal/polyacetal.
Femoral (hemi-hip) prosthesis - metal/UHMWPE.
Acetabular (hemi-hip) prosthesis - metal.
Femoral (hip) resurfacing prosthesis.
Pelvifemoral (hip) resurfacing prosthesis - metal/polymer.
Constrained femorotibial (knee) prosthesis - metal.
Non-constrained Femorotibial (knee) prosthesis - metal/composite.
Semi-constrained Femorotibial (knee) prosthesis - metal/composite.
Constrained femorotibial (knee) prosthesis - metal/polymer.
Non-constrained femorotibial (knee) prosthesis - metal/polymer.
Semi-constrained femorotibial (knee) prosthesis - metal/polymer.
Femoral (hemi-hip) prosthesis - metal.

Source: James G. Dillon, Bureau of Medical Devices, Food and Drug Administration clinical data needed, though, have not been determined. Furthermore, because joint implantation and bioengineering are young, inexact sciences, the first four requirements have been sources of contention between the FDA and the manufacturers.

It has become apparent to the FDA and the implant industry that the era of 510(k)'s may be nearing an end. There are only a limited number of variations that can be made to existing technology. Research has not stopped and many ideas in laboratories cry out to be tried in newly designed joint implants. Yet, at the time of this writing there has not been a single joint implant PMA submitted to the FDA for approval (21).

Manufacturers have been reluctant to introduce an implant for a number of reasons. At present, manufacturers must obtain an Investigational Device Exemption (IDE) prior to using a new device in patients. If a 510(k) is denied, much of its contents can be used when requesting the IDE. Once in hand, manufacturers can organize, execute, and analyse the data generated in clinical trials. As required by the Amendments, the data must demonstrate the safety and effectiveness of the new device to the satisfaction of the Advisory Panel and ultimately the FDA. Very broad regulations have been issued for both the IDE's and the PMA's, and are intended to cover any device that may be submitted for review. It is the responsibility of each section of the Bureau of Medical Devices (BMD) to issue specific guidelines with respect to devices in their jurisdictions. Currently, the Orthopaedic Section is using guidelines written by the BMD for general use by the different Sections, without modifications. There are no guidelines available tailored specifically to the needs of the makers of joint implants (21,72). Without such guidance, manufacturers have been hesitant to enter the PMA process (3,31,54).

A result of the Medical Devices Act can be seen in the kinds of implants available between 1976 and the present. Over the past five years, there have been no new materials introduced for artificial joints. Materials such as the carbon-impregnated polyetheylene recently marketed were in existence prior to 1976. Marketing of a shoulder implant has been prevented repeatedly by the FDA, partially because of disagreements between manufacturers, investigators, and the FDA over the adequacy of collected data (21,73). Biomet Inc., which is a two year-old firm, has only introduced devices under the provisions of the 510(k). Biomet Inc. lacks the funds and also the assurances from the FDA that any clinical trial it may propose, execute, and analyze, will remain valid and acceptable six years following submissions to the FDA as supportive evidence for a PMA.

The Custom Device Provisions of the Medical Devices Act are another means manufacturers use to avoid the PMA process when releasing a new implant. Under them, physicians and manufacturers can gain approval for implants, either new ones or adapted old ones, if they are shown to be the only solution to an individual patient's situation. These devices are individually (custom) made for the patient and the company is not allowed to mass produce them. The provisions have been used by the manufacturers to release new devices and test them without going through the PMA process.

Implant manufacturers scrutinize new implant designs more carefully than ever before because of the Amendments. To some extent, the intent of law is to prevent unproven or unsafe devices from entering the market and harming people. However, orthopaedists do not have a satisfactory alternative for evaluating a new device besides actual use in patients. With reservations about the future of PMA's, manufacturers have moved their research and preliminary device investigations outside the U.S. New materials and designs are currently being tested in other countries, sometimes in cooperation with foreign manufacturers. Once these firms establish the value of their products elsewhere, they may try to reintroduce the device here (3,24,31).

One clear benefit from the Medical Devices Act has been greater attention to quality-control procedures within the industry. However, the manufacturers repeatedly imply that the FDA does not appreciate the nature of the device manufacturers. A example cited is the requirement by the FDA for firms to document breakage of a drill-bit. If a device is rejected anywhere along the production path, complete records must be kept as to the disposition of the device, including the reasons for its rejection. The manufacturers perceive such requirements as indicating a poor understanding of the device manufacturing world (3,24,31).

The controversy and uneasiness between the FDA and the manufacturers and orthopaedists promotes the general impression that the FDA is impeding innovation of new joint implants. A frequent remark made about the FDA refers to the FDA's inability to comprehend the problems of medical device technology. Historically, this may very well have been true. The BMD formed with FDA personnel whose expertise naturally rested with the regulation of drugs. Therefore, they were largely specialists in areas such as biochemistry and pharmacology. The early days of the BMD could very well have been a proverbial Tower of Babel, with industry engineers trying to discuss critical regulatory issues with BMD chemists and biologists. The language and concepts of those two worlds are vastly different and the problems in communication were probably frustrating for both sides (21,26,53,63). The manufacturers believe that the BMD will continue to regulate without truly understanding the differences between devices and drugs and the differences between adequate device regulation and adequate drug regulation (3,24,31,54,63).

Since the creation of the BMD in 1974, the FDA has in hired staff members capable of comprehending the issues and concerns of device manufacturers. As of March 1981, there are 168 scientists on the BMD staff of which 56 are engineers. Of them 27 are assigned to review premarket requests and IDE applications, as well as participate in the ongoing classification of devices (65). The Orthopaedic Section has five science staff members, three of which are engineers. In order to better familiarize the Orthopedic Section with the uses and problems associated with orthopaedic devices, arrangements have been made for field-trips to Johns Hopkins Medical Center to see orthopaedists work in the clinics and in the operating room (21,62).

The FDA has not completed the task of organizing and administering the Amendments of 1976. Until that task is completed, it may be unwise to say more about other aspects of the agency's policies and direction. Policies already discussed may change in the future as experience with the laws accumulates, and the FDA settles into its new job of regulating medical devices.

Chapter 11

Some Legal Considerations of Joint Implant Technology

11. SOME LEGAL CONSIDERATIONS OF JOINT IMPLANTATION TECHNOLOGY

In the instance of medical device technology, and in particular joint implants, the legal considerations are intertesting but not unusual (G). Civil law plays a role in the inevitable dissatisfaction of some recipients with their joint implants, when the device fails. Civil law provides an avenue to assess retribution.

A function of the courtroom is to help establish which parties are responsible for the damage claimed to be suffered by the plaintiff. Was the product at fault? Was the surgeon at fault? Or, can no fault be established? It stands to reason that a pivotal point in such a determination is the nature of the failure and the evidence about the failure of a device. With those basic points in mind, a liability case in the realm of joint implant technology requires the expertise of: lawyers, surgeons, bioengineers, manufacturing engineers, and other specialists who bring a vast body of knowledge, experience, and controversy into the courtroom. It is then the charge of a lay jury to provide justice.

Implant Retrieval Analysis

Bioengineers play a critical role in such litigation by determining to the best of their ability the cause of failure (82). There are numerous ways in which a device can fail. Mechanical failure can occur when a device is overloaded and stressed beyond its limits. A device can suffer from fatigue failure because of repeated cyclic loading of the device which eventually stresses the device beyond its limits. Devices can fail due to wear, in a fashion similar to that of a pair of old shoes. The device can undergo environmental failure in the complex and relentlessly unforgiving chemical pool known as the human body. Of course, one or any combination of the failure modes outlined can occur simultaneously which can confuse the picture considerably (71).

Retrieval analysis has been alluded to repeatedly in this paper and is an important part of implant bioengineering because of its importance to the design and evaluation of implants. Sophisticated retrieval programs depend on a well-organized and cohesive approach to such analysis. Bioengineers work hand in hand with surgeons once a failure has occurred in order to maximize the amount and quality of information that is gathered about the device. Data needed includes: patient history both at the time of implantation and removal, X-rays of the implanted device, the level of activity engaged by the patient, the device itself, and the manufacturer's identity and device serial number. Bioengineers examine and analyze the device using a host of engineering tools. Tissue samples from the patient are also supplied by the surgeon at the time of device removal in order to obtain further clues as to the events occurring in the body (82).

With the gathered data, bioengineers try to address the questions of failure, not only to improve the device or to inform the surgeon of a potential problem, but possibly to explain the situation to a jury in a liability case. What were the mechanisms of the failure? To what factors can the failure be ascribed? Was the device improperly manufactured? Was the device implanted incorrectly? Did the recipient overuse the artifical joint? At present, retrieval analysis is more an art than a science. There are large gaps in the understanding of the information gathered from such analysis. Therefore, in the courtroom it is not unusual to find two distinguished and reputable people disagreeing on the conclusions drawn from an evaluation of a removed failed implant (82). In many ways the litigation of an implant failure case for product liability, malpractice, or both, is an exercise in which the winning side has the "better" experts (46).

In the early days of joint implantation, questions were raised with regard to the ownership of a retrieved device (71). It has been repeatedly held by the courts that devices are sold to patients and clearly belong to them. Therefore, if surgeons or bioengineers wish to retain the retrieved joint for study purposes, proper consent from the owner (the patient) must be obtained. It has become evident to investigators that liability suits may arise requiring data from the device. Researchers take great care not to destroy devices while analyzing them, in consideration of the potential for future litigation (82).

A conflict among lawyers, patients, manufacturers and surgeons arises in determining where a liability suit is to be tried. If plaintiffs (the patients) wish to press product liability suits, they can have the suits filed and tried in the State where the device was purchased, or in the State in which the device failed. If plantiffs are planning malpractice suits, they can only be filed and tried in the State where the medical services were provided. If a State happens to require mandatory arbitration prior to such malpractice suits, and plaintiffs wish to pursue a product liability suit as well, the arbitration panels cannot rule on the product liability issues. Therefore, plaintiffs would be required to have product liability suits tried separately. In States without such arbitration panels, both medical malpractice and product liability suits could be conducted simultaneously in the court. At present, the law does not provide relief in these overlapping areas of jurisdiction.

The industry defends itself against a product liability suit in a fashion similar to other industries selling other products; the laws and theories are the same. Device manufacturers do not provide explicit warranties with their products for the obvious reason that they do not control the manner in which the products are used by surgeons (81). Common law, however, holds manufacturers responsible for all implied warranties established over the years. In a similar fashion, surgeons and their legal advisors defend malpractice suits, without regard to whether an implant was used, because the laws and theories of medical malpractice are the same in joint implant surgery as they are for other medical specialities.

A relatively new concern for manufacturers is the liability for products on a Federal level, under the provisions of the Medical Devices Act. Now, besides being responsible for a product's performance on the State level, the industry has the added responsibility to comply with Federal laws and regulations under penalty of the law for failure to do so. There is a special interest in this overlap of responsibility. A product liability suit in the future may not only draw attention to responsibilities under implied warranties, but also upon the compliance of manufacturers with Federal laws and regulations. This would add a Federal lawsuit to a case that once was tried in the State courts. Furthermore, the Government could be sued in such a liability case for its role in enforcing the Amendments and related regulations. The significance of such cases has not been tested in the orthopaedic implant field as of yet.

It is important to stress that legal considerations with regard to artifical joint implants are not unique or unusual as compared to other products or medical services. There are some inconistencies in the laws from State to State, and the added legal questions accompanying the Medical Devices Act need to be answered. The fact remains that the obligations and responsibilities of implant manufacturers, and surgeons, as well as hospitals are well defined in the law, but often very difficult to demonstrate in the courtroom.

Chapter 12
Analysis

12. ANALYSIS

Of importance to all policymakers are accurate estimates of the medical technologies under discussion. These have not been made in the case of joint implant technology. The article discussed in the Introduction (39) by Hori, et al., is the only documented effort to demonstrate the extent of device proliferation in the United States, and this effort is by no means flawless. The statistics obtained by the authors were not controllable for accuracy nor for completeness. The authors could not verify whether or not collected data strictly adhered to the definitions of the surgical procedures being assessed. As noted in Chapter 9, early data on total joint surgery did not carefully differentiate the various joint operations available. Sales data from manufacturers does not take into account the number of devices remaining on the shelves in distribution centers and hospitals. The authors extrapolated regional figures in order to derive national statistics. But without the ability to inspect the methodologies used, readers and users of this data cannot be certain that the extrapolations are correct. Finally, the report is outdated by almost 6 years (the last figures supplied were for 1976). If the subjective impressions of people involved in joint implant technology are correct, there has been a substantial gain in the number of such procedures done since that time. Without accurate detailed estimates of the pervasiveness of this technology, effective policies and decisions cannot be made.

Patient Involvement

As a technology directed towards the handicapped, joint implantation holds the promise of greatly restored function for those formerly treated as chronically disabled. There are few, if any, implant recipients actively involved in aspects of this technology. Patients are "passive" participants in the evaluation of prostheses. They are provided with these joints by surgeons, who assess the subjective results, as well as formal measures of their function, which forms the basis for determinations on the adequacy of the devices, as described in Chapters 2 and 5.

Patient demand exists for artificial joints primarily because knowledge of their existence is widely known. However, this demand is not organized nor is it influential on this technology. The true consumers of this technology are surgeons; they consider these devices as a form of therapy, to be prescribed and administered in the traditional medical manner.

Patient satisfaction is not directly addressed in the medical literature, rather it is inferred indirectly in data on device performance. Only one article reviews devices from the perspective of patients (H). It examines the preoperative expectations of hip recipients and compares them to the results that patients obtain, and their reactions. When expectations and final outcomes do not coincide, lawsuits may result. There is little doubt that some patients harbor excessively high expectations with regards to the performance of their new joints. Interestingly, there are no patient support organizations for implant recipients. The support network in place for arthritics does not actively act on behalf of such recipients.

A formidable problem encountered with respect to patient expectations and the physicial demands placed on joint devices, is the lack of adequate implants for young patients. Orthopaedists routinely state that young patients (under ages 45 to 50) are not suitable candidates for these devices. As discussed in Chapter 4, the potential for excessive stress placed on those joints can lead to premature failure requiring revision, or even worse, joint fusion. The risks of the technology outweigh the benefits. Orthopaedists feel very strongly about this issue and many consider implanting young people to be malpractice. Is it for the surgeons alone to determine the benefit/risk ratio for this technology? If young people agree to restrict their activities, should surgeons implant them? Would surgeons be risking malpractice liabilities if they did so? Should surgeons offer the joints to patients that need them, and allow the patients to do as they please, since its their lives?

Removing Obstacles to Progress

The safety, but more importantly the effectiveness, of joint implants has always been a major concern. In order to make such determinations, information must be collected and analyzed, information gaps must be recognized and addressed, and the synthesized information must be distributed to those that need it.

The information presented in Chapters 3 and 5 typifies some of the current methods employed in medical technologies, including joints. Instead of planning and executing well-designed prospective clinical trials, information on joint implants has been collected from the analysis of clinical experience.

Various commonly used descriptors -- mild pain, good function, can walk less than 30 minutes, etc. -- are poorly defined by the investigators using them, if they are defined at all. What is 'good function?' How does a patient characterize 'mild pain?' Is good function in a 75 year-old man the same as good function in a robust 45 year-old woman, both of whom received the same knee replacement? Is mild pain for one person, mild pain for another? The descriptors and the questions can go on for pages. The systems currently in use do not clearly and explicitly define such subjective criteria, which is so critical to the results reported by the investigators using replacement devices.

A closely related matter concerns the methodology used by the researchers to get the data. What questions are asked to determine if the pain is mild or moderate? Who asks the questions? Is the same interviewer used preoperatively and postoperatively? What is the bias of the interviewer? Questions such as these pose serious problems with regard to the objectivity of the results reported. In many cases, the treating surgeon or a member of the treatment team closely involved with the surgeon gathers these responses. There is no way to determine how an interviewer's biases affected patient responses. Readers cannot be sure that patients were totally honest when confronted by their treating physicians with questions about the success of their operations. There is no guarantee that each patient in a study was questioned in a manner similar to other patients.

A deficiency in the literature, closely related to the problems already discussed, stems from the fact that numerous systems for evaluation are in current use across the country. Each system uses its own numerical scale, has criteria which may be similar in some respects to others, and is felt to be the best way to access a patient by the group who devised it. It is frustrating to attempt comparisons between different studies. For example, the study from the Mayo Clinic on the Anametric knee uses a numerical system which grades results from 1 to 10 for pain, function, and walking. Setting aside the issues of definition, there is little doubt that the results as presented are easy to appreciate and comprehend. But, it cannot be used for comparison with earlier data generated at the Mayo clinic on the geometric knee. That evaluation system was descriptive -- the pain was mild or moderate, function was good, and so on. The net effect is that the data on the Anametric knee is isolated from the data on its predecessors.

Many other controls are missing from total joint replacement articles found in the medical literature. Information offered about knee and hip prostheses are anecdotal to a large degree. Even the simplest statistical controls are not used in these studies. Variations in sex, age, disease, level of activity, and overall medical condition are not factored into the results reported. It stands to reason that groups of patients that are younger, vigorous, and enthusiatic may provide very different results from groups that are old, with other diseases when both receive the same artificial joint.

A common rebuttal to the issues raised notes that few in the orthopaedic community defend the methodology and techniques employed in the past to collect data on the knee or hip however, it is pointed out that both hip and knee technology is in a rapid state of flux. Orthopedists argue that undertaking long prospective well-controlled trials, using devices which may change long before the trial is over, is a waste of effort, time, and money. A common feeling expressed by many is that the data generated by present reports is helpful in quickly finding the major faults in the design and/or surgical instrumentation of a device. Such reports do not conclude that new devices are a panacea to all that ails patients, nor do they imply that the search for yet better devices has come to an end. Many feel that once stability is reached in the design and understanding of both knee and hip joints, efforts can be directed to weed out marginal devices that may not measure up to future standards.

There are numerous areas where information is particularly lacking. These areas are clearly stated in a document released by the American Academy of Orthopaedic Surgeons (AAOS) in February 1981. An important research goal is to minimize the rate of device failure due to loss of fixation between polymethyl methacrylate (PMMA) and the bone. Better techniques need to be designed to evaluate stresses in artificially implanted joints. Gait analysis studies, transducers, and telemetry systems are methods which have promise and need further investigation. Improvements in cement and the search for alternative cements must continue. Alternatives such as porous ceramic surfaces (for bony ingrowth) must also be explored to reduce rates of mechanical loosening. Finally, bioengineers and clinical investigators must be trained in order to pursue research projects essential to the continuing improvement of artificial joints. Close collaboration between scientists and clinicians is central to the enhancement of joint implantation.

Federal polices related to safety and effectiveness for artificial joints are similar to those of other medical technologies. As intended by the 1976

Amendments, the industry has been given full responsibility to prove safety and effectiveness. But Federal policies have poorly defined "effectiveness." What is the valid "scientific evidence" necessary to show that a Class III device is effective? Only the Food and Drug Administration (FDA) has been given a statutory definition, under the 1976 Amendments, of safety and effectiveness. The difficulties being encountered by the FDA in arriving at workable standards is exemplified by the fact that specific guidelines for premarket approvals (PMAs) are not available for artificial joints. There is a controversy among orthopaedists and bioengineers about this very issue. What kind of methodology would be acceptable to the FDA? How will the FDA set the standards for guidelines on clinical trials and acceptable forms of data?

Even with such questions answered in the future, there is no mechanism for making safety and effectiveness definitions uniform among all Federal agencies. Some agencies develop information on safety and efficacy, other's disseminate the information synthesized, and others regulate different aspects of medical practice. Lack of uniform policies, as definitions become available, only leads to confusion and communication difficulties. Currently, there is no formal policy or agency responsible for overseeing such a task.

The dissemination of data gathered on medical technologies (i.e. artificial joints) is typical (see ch. 9). The Federal agencies using such data have no formal methods of collecting the best data available. The medical literature, with all its drawbacks, acts as the information backbone of these agencies. The ability of Federal agencies to collect good information is dependent on their willingness or financial ability to obtain it. An indication of the severity of the problem can be seen in the fact that the FDA did not send a representative to the AAOS annual convention in Las Vegas in 1981. The data presented there on devices (all of which are FDA-regulated), will not be readily available for some time and when it finally appears, it may already be out of date. The reason the FDA did not send a representative was the lack of funds.

The ability of the private sector to move forward and bring improved medical technology to the population has been a concern especially as it relates to government policies. As in other medical technologies, this issue is important to joint implantation. The innovative processes (a term which has yet to be adequately defined) in joint implantation occurs in three broad areas: surgical techniques, device designs, and manufacturing techniques and new materials, as discussed in Chapters 2 and 5. New joint technologies have been hampered by gaps in knowledge and industrial capabilities, as well as by the relatively low level of funds available for basic and applied science research. As noted in Chapter 9, several agencies actively provide funds for such research. However, those funds are not in proportion to the monies expended annually on the treatment of diseases addressed by joint replacement. Federal policies address the "needs" of the population in terms of medical care, but do not actively encourage a proportional amount of research, especially when compared to other medical endeavors such as kidney diseases or diabetes.

A problem plaguing Federal agencies is the lack of interagency coordination, (see ch. 9). The response of other Federal agencies to National Aeronautics and Space Administration's (NASAs') inquiries on the University of

California at Los Angeles-Jet Propulsion Laboratory of the California Institute of Technology (UCLA-JPL) hip telemetry project was not enthusiastic. The subsequent funds spent by NASA for development of the technology may have been wasted. At present, the project's coordinators are looking for renewed Federal sponsorship. The incident illustrates that there is no uniform centralized method of evaluating proposals and projects in the the Federal Government that cut across agency jurisdictions. Each individual agency zealously pursues its own mandates and interest without the necessary incentives to closely cooperate with other agencies. With the current funding atmosphere and the poor coordination between agencies, there is reason to believe that such incidents will be repeated, thus stifling potentially valuable research, as well as squandering Federal funds on half-completed projects.

The innovative process has been strongly influenced by the Amendments of 1976 to the Food, Drug and Cosmetic Acts, and by the regulations promulgated by the FDA for its administration and enforcement. As discussed in Chapter 9, there have been no new and revolutionary joint implants introduced in recent years, as indicated by the lack of PMA's submitted to the FDA for approval. The difficulties in defining safety and effectiveness affects devices in the Class III category (such as joint implants) the most. The controversy over the requirements necessary to gain approval for joint implants under the PMA process, in conjunction with the safety and effectiveness debate, contributes to the hesitancy on the part of industry to undertake applying for premarket approval. There is an underlying fear that the FDA will change its policies over the coming years, leaving manufacturers, who are financing and conducting clinical trials, "holding the bag" if their studies are deemed unacceptable.

In an atmosphere where the implant industry is very hesitant to embark on a course leading to a PMA application, the Custom Device Provisions of the Medical Devices Act has become an approach through which they try new ideas. Under those provisions, the manufacturers have experimented with numerous devices. Some of these have shown promise and may be marketed in future years. But the bulk of research by manufacturers in areas such as man-made materials, has moved out of the country in a fashion similar to drug development and testing. Manufacturers and innovators have chosen not to wait for Federal policies on safety and effectiveness, as well as policies on the administration of Amendments, to become well-defined and consistent before conducting further research.

Linking the provisions of custom devices and the uncertainty over the future of the PMA process, is the FDA approach to low-volume device technologies. Currently, there is no stratification of requirements for premarket approval, separating low-volume from high-volume devices. Some implant devices, such as artificial shoulders (I) have very small markets. Should such devices be put through the same rigors as a high-volume device? What can be done if a low-volume device becomes popular and turns into a high-volume device? The lack of Federal policies in this area has prevented the release of some devices, and the development of others because the costs to develop them and have them approved under the PMA process cannot be offset by the future sales.

An interesting paradox, often overlooked, is the potential conflict between patent statutes and the 1976 Amendments. Because the provisions of the 510(k) require that a device be "substantially equivalent" to a prenactment device, it stands to reason that the devices are not "new or original." Therefore, they should not be afforded patent protection. If devices are eligible for patent protection, then they are not "substantially equivalent." The dilemma for the manufacturers has not been seriously experienced because patent protection has generally been poor for implant devices in the past. But the elements of a conflict are present and if not addressed through policy alternatives and changes in the laws, legal battles will eventually resolve the issues.

Appendix: Analysis of the Article:
"An Economic Evaluation Of Premarket
Regulatory Requirements," by Eldon Frisch

APPENDIX

Analysis of the Article: "An Economic Evaluation of Premarket Regulatory Requirements," by Eldon Frisch

The manufacturers of orthopaedic devices perceive themselves as providers to surgeons of service in the form of dependable surgical equipment for use in the treatment of their patients. The better the service, the better the sales, and the larger the profits. Some in the artificial joint implant industry view the costs of complying with the Amendments of 1976 as far in excess of the benefits derived from its provisions. They do not view costs solely in terms of the financial burdens imposed, for those can be easily passed on to the consumer. They also view the costs in terms of innovation, and the lack of it, in today's regulatory environment (3,24,27,63).

In general, the device industry perceives that the investment required to develop and gain approval for a device is not always proportional to the number of devices sellable. They repeatedly emphasize that the regulations do not distinguish between low-volume devices (say 50 devices sold per year), and high-volume devices (say 10,000 devices sold per year). For both types of devices the total regulatory cost would be similar, yet the sales of the low-volume device would never approach the levels necessary to recoup the costs.

This issue and others are primarily directed at the premarket approval (PMA) requirements of the Amendments, and its administration by the Food and Drug Administration (FDA). The costs associated with a PMA has been debated extensively since the early 1970's (63). However, little documentation of those costs has been made public, if it exists at all. The article reviewed is the only attempt available in the literature to estimate such costs.

In the years prior to enactment of the Medical Devices Act, arguments against the law, on the basis of excess costs to manufacturers (and ultimately consumer), were commonplace (63). It would seem reasonable that some manufacturers now know the extent of such costs because the information is needed to make initial decisions with regard to developing new products, such as artificial joints. However, it is evident that artificial joint implant manufacturers cannot or will not publicly estimate cost (3,37,54,63,83).

In October 1980, an article published in "Medical Device and Diagnostic Industry" appeared on this topic 4.5 years after the enactment of the 1976 Amendments. Written by Eldon Frisch, this article is the only piece of its kind on the Medical Devices Act and its cost in the literature. Yet, with 4.5 years of experience with the devices legislation, this article only speculates on those costs without citing hard facts or past actual experience.

The article compares the regulatory costs of bringing two hypothetical devices to the marketplace. Mr. Frisch notes that the devices' composition and manufacturing techniques are "well known and similar" to devices long on the market. Presumably, he does this to eliminate these criteria from being used in classifying the devices by the FDA. The criteria remaining, then, are those related to design, intended uses, and so on. Mr. Frisch does not clearly distinguish between the device intended for the Class II category from the one intended for the Class III category. The readers must assume that these hypothetical devices proposed by the author are not totally unreasonable (21,37,63).

To be placed in the Class II category, the device would be "substantially equivalent" to devices on the market prior to the enactment of the Amendments. The manufacturers are only required to notify the FDA of their intention to introduce the device under the provisions of the 510(k) regulations. The device in the Class III category would be ruled substantially different by the FDA, thus requiring the manufacturers to submit a PMA for approval. The intent of Mr. Frisch's article is to compare the costs of these two regulatory routes.

Mr. Frisch assumes that the basic development costs for the device is $250,000. The cost is only speculation, since the device is hypothetical. He also calculated accrued interest costs on borrowed funds at a rate of 15 percent, totally reasonable in the present economic climate. Finally, Mr. Frisch estimates that 9700 devices will be sold over the first 3 years of sales after FDA approval. Because the device being discussed does not exist, the level of sales expected cannot be verified. Therefore, 2 of the 3 key assumptions made at the outset must be taken for granted without an understanding of the device being discussed. Is the device directed at a very limited disorder and therefore it has only a small potential market? Is the device competing with numerous other similar devices, thereby only commanding a limited market share? The distinction can be important in determining the design of a clinical study needed to establish the safety and effectiveness of the device. A low-volume device may be tested on fewer people than a high-volume device. The cost to develop the device, $250,000, is important because it is used to determine interest charges accrued while regulations are being obeyed. Nevertheless, the device, its costs for development, and its potential saleability must be accepted prior to analysis of the regulatory costs.

In determining the costs of the Class II devices approval, Mr. Frisch notes that the delay in marketing is 6 months. This may not be the case. If readers are to assume the device is truly "substantially equivalent" to a prenactment device, then they must assume the FDA will concur. The Act and the 510(K) regulations require notification within 90 days of the intended date of marketing the device. The FDA must act on the notification within the 90 days and approval allows sales to begin immediately after. Mr. Frisch assumes that the manufacturer is unsure of FDA approval and therefore, waits for official approval prior to investing and undertaking the final commercialization steps needed for sales. Many manufacturers of joint implants often communicate with FDA informally and have some notion of their standing with regard to a specific product. The future course of events for most devices probably lies between the two extremes. Some devices are probably commercialized while the 510(k) is pending, others are left in earlier stages until approval is given. Based on a 6 month delay in commercialization, Mr. Frisch calculates the costs of the 510(k) to the manufacturer to be $2.74 per device over the 3 years of sales for which costs are to be recouped (based on the sale of 9700 devices total).

The cost estimate of the Class III device is more complex and relies on several more assumptions. The PMA must demonstrate to the FDA that the device is safe and effective. But PMA regulations and guidelines are not fully implemented, therefore, Mr. Frisch's discussion is based on anticipated regulations and guidelines to be promulgated in the future. The Amendment requires some form of scientifically valid evidence (such as a clinical trial) to make the determination of safety and effectiveness. Mr. Frisch determines that 5 clinical investigators are needed to conduct a trial on the hypothetical device. But without knowing the incidence of the disease to be treated with the device, and the number of available research centers treating the disorder, this assumption cannot be verified. There is little question that less than 5 investigators would not be used no matter what the disorder. Therefore, the cost estimates for such a study are low, rather than high.

A similar problem exists for the subjects expected to participate in the trial. Mr. Frisch determines that 75 such subjects are to be recipients of the device with a followup attrition rate of 33 percent over the life of the study. Without precedents set from previous PMA's, Mr. Frisch cannot be certain of the appropriate study size. As of this writing, the FDA has not established appropriate study sizes for devices testing (21). Nonetheless, the figure proposed by the author seems small, rather than large, causing the final cost estimates to be low again. Mr. Frisch estimates the costs of each investigator grant ($3,000), fees for filling out forms ($100/form/patient), fees for each X-ray ($30) and administrative costs for the study ($55,000/year). All these estimates seem reasonable if not conservative (3,26).

Mr. Frisch assumes that it will take 6 years to conduct the clinical study. He requires tht at least 2 years of followup be available for all patients in the study. In general, orthopaedists and the industry agree on this, based on past experience with joint implants (3,26,37). In fact, a recent Orthopaedic Advisory Panel meeting held in March 1981 reiterated this point (73). However, the FDA has not taken an official position on this issue. It could easily take 3 years to accumulate 75 patients in a study, depending on the device and the diseases it treats (26). With 2 more years to organize, analyze, and submit the PMA to the FDA, the entire study could easily span 5.5 years. In addition, the Amendment allows the FDA 180 days to consider the PMA, or more if clarifications are requested. Mr. Frisch correctly assumes that 6 years would pass from the time the device is ready for testing until the time the FDA approves it for release.

Mr. Frisch calculates the cost to the manufacturer of the PMA to be $859,098 total, adding a cost of $125.36 to the device over the first 3 years of sale of the 9700 devices. Several key questions could be asked at this juncture: 1) Wouldn't the manufacturer have incurred some of these costs for a clinical trial regardless of the FDA? 2) What was the cost and the selling price of the 75 devices used in the study? The answer to the former is a resounding no! Orthopaedic investigation around the country reveals that the manufacturers did not participate in clinical trials in the past years and testing of joint implants has been the expense of orthopaedists and their respective universititeѕ and/or medical centers in the past. The manufacturers have helped develop the device design for production and may have provided the surgeon/designer with prototypes for early testing. It has been the case that the clinical trials of such devices found in the medical literature were supported with funds not derived from the manufacturers. The devices used in those trials often were sold to the patient or third-party payer rather than donated (26, 77). One effect of the Medical Devices Act has been to force manufacturers to consider bearing the costs of such trials because it has become evident that orthopaedists will not. Orthopaedists are well aware of the fact that drug manufacturers had been paying for clinical trials for use by the FDA and orthopaedists have come to expect the same from the device manufacturers. The second question posed above is not addressed by the author at all. It seems that this omission is significant. But many other assumptions are clearly conservative and the overall effect of this neglected factor is probably slight.

The dollar difference between the cost of each Class III device and the cost of each Class II device due to regulatory effect is $122.62, or it costs 45.7 times more to gain approval of each Class III device. That amount is reflected in the devices sold in the 3 years after introduction to the market. If Mr. Frisch had concluded his article on that note, this study would have been interesting, but vague in its conclusions. Unfortunately, Mr. Frisch continues and calculates the market multiplier-effect on the manufacturers expense of complying with the Medical Device Act. The premises used by the author may be incorrect and manipulative, possibly leading readers to reconsider other assertions made in the article as well.

As Mr. Frisch correctly notes, the cost-to-selling-price multiplier (cost plus pricing) is a method of considering the many costs of doing business as a single factor, with different factors which can be compared to determine the impact of a particular cost on the final selling price. His detailed analysis is essentially viable, up to the circle graph provided in his Figure 1. The author effectively defends the "selling" expenses for the medical device of 40 cents on the dollar. The fact remains that selling expenses and the final sellers' profit are controlled by the market's price tolerance. Therefore, the mark-up in price and the selling costs are closely linked and highly variable depending on the product. It is certainly possible to have as much as 40 cents per dollar devoted in that area, but not necessarily so.

The crux of the problem arises in the 60 cents portion of the circle graph: allocated costs (21 cents), marketing costs (6 cents), R&D costs (6 cents), profits (9 cents), and finally the fixed and variable manufacturing costs (18 cents). The distribution of those costs and expenses are not justified in the text of the article. The postulations by Mr. Frisch must be taken at face value; a hypothetical allocation of business expenses and costs for a hypothetical device. Just as disturbing, the author chooses to include the one-time regulatory costs for the device in the fixed costs of manufacturing, along with the machinery, plant costs, and engineering outlays, and he does not provide the proportion of the manufacturing costs attributable to the regulations. Since Mr. Frisch proposes to recoup the costs of regulation in 3 years, does he intend the same with all the other fixed manufacturing costs? Obviously not. The final price of the device would probably be too high for the market to bear. It is interesting to note that Mr. Frisch also includes under the fixed manufacturing costs -- the development costs. What development costs? In the circle graph, a separate category has been assigned for the expenses for research and development (R&D). Is there a difference between the two? Questions such as those are unsettling and raise serious doubts about the validity of the entire multiplier position presented.

It is common to use manufacturing cost as a basis for determining the final selling price, since "those costs are clearly incurred and need to be recovered." Some would probably place regulatory costs together with the cost of product development, not the cost to manufacture them. To treat the regulatory cost with a multiplier derived from the manufacturing costs is unacceptable. The results of such a maneuver by Mr. Frisch is a device priced $19.04 more due to Class II regulations, and $871.25 more due to Class III regulations. He notes that a device selling for $250.00 (prior to regulations) would sell for $1,125.25 under the regulations, an impressive and shocking figure. It is apparent that the methodology used by Mr. Frisch to arrive at the final-price increase directly attributable to regulatory burdens is faulty.

There are other issues that Mr. Frisch avoids in determining the costs of the regulatory burden on manufacturers. Since the article is intended to only discuss the premarket requirements, though, the omissions are to be expected. The article speculates on the cost to the manufacturer of complying with the premarket approval requirements legislated by the Medical Devices Act. It is not based on actual costs incurred by a manufacturer undergoing the PMA process, even though 4.5 years have passed since enactment. There are two critical assertions with regard to the device: developmental costs, and anticipated sales level for the device, which have a central bearing on the figures generated by the author. The assertions are fictitious, therefore, they cannot be accurately verified. The cost per device to the manufacturer is calculated to be $2.74 for the Class II device, and $125.36 for the Class III unit (based on 9700 units sold over 3 years).

The criteria for estimating the delay in the marketing of the Class II device were slightly inflated, and the cost is probably lower than predicted. The assumptions used for developing and conducting the clinical trial were reasonable, if not somewhat conservative, thereby holding the predicted costs down. Mr. Frisch attempts to arrive at the final consumer costs for the device by using the price-multiplier technique. He incorrectly assigns the regulatory cost to the fixed manufacturing cost category, thus justifying the use of the manufacturers cost-multiplier to determine the increase in regulatory cost seen as the final selling price for the device. It is certainly more correct to assign the regulatory costs as part of the one-time product development costs.

Disregarding the drawbacks to the multiplier arguments, this article is the only available documentation of the potential costs of the Medical Device Act. The scenario depicted by Mr. Eldon Frisch is not far-fetched and may very well reflect reality. But it would certainly be more valuable for manufacturers of such devices to carefully account for all the costs incurred while complying with FDA regulations under the Medical Devices Act, in a controlled fashion. Presentation of such data would be extremely valuable to policymakers trying to assess the impact of Federal laws and regulations on this industry.

Footnotes

Footnotes

A. Some of the data and manufacturing procedures outlined are this writer's impressions while conducting on-site visits with the following firms: Biomet, Inc., DePuy, Inc., O.E.C., and Zimmer-USA, in Warsaw, Indiana in March 1981.

B. Most of the data on man-made materials is derived from discussions with Dr. A. Burstein and from: Calandruccio, R. A., "Anthroplasty," in Campbell's Operative Orthopaedics, ed. by Edmunson, A. J., and Crenshaw, A. H.: C. V. Mosby Co., St. Louis, 1980.

C. These historical notes are summarizations of accounts provided in: Walker, P. S., Human Joints and Their Artificial Replacement, Charles C. Thomas, Springfield, Illinois, 1977.

D. The term 'medical indications' as used here, refers to diseases that have the potential of causing severe joint damage leading to the possibility of joint replacement. Most of the data was derived from: Calandruccio, R. A., "Arthroplasty," in Campbell's Operative Orthropaedics, ed. by Edmunson, A. J., and Crenshaw, A. C.: C. V. Mosby Co., St. Louis, Mo., 1980.

E. Views attributed to orthopaedic implant manufacturers on the FDA and the Amendments of 1976, are composite impressions of this writer, based on numerous discussions with industry representatives between February and April.

F. This description of the Amendments of 1976 is derived from several sources: Banta, D. H., Brown, S., Behney, C., "Implications of the 1976 Medical Devices Legislation," in Man & Medicine, 3:131, 1976; Dr. James Dillion, Executive Secretary of the Orthopaedic Section, Bureau of Medical Devices, Food and Drug Administration; The National Archives of the United States, The Federal Register, Department of Health, Education and Welfare, FDA "Medical Devices," vol. 43, no 146, Book 2, Friday, July 28, 1978, Part II.

G. The legal considerations outlined in this section was made possible through the generous cooperation of Mr. Rom Lemmon, legal counsel for Zimmer-USA of Warsaw, Indiana. The information supplied is based on several interviews conducted in March and April 1981 with Mr. Lemmon.

H. Burton, K. E., Wright, V., Richards, J., "Patient Expectations in Relation to Outcome of Total Hip Replacement Surgery," Ann Rheu Dis, 38:471, 1979. A literature search did not turn up any other similar articles.

I. Richards, Inc., reported to the Orthopaedic Advisory Panel in March 1981 that it had only sold 400 artificial shoulder joints (the Michael Reese Prosthesis) over 8 years which is an annual sales rate of 50 devices per year.

J. Addendum. For a good epidemiological cost estimate analysis on hip arthroplasty see: Metton III, L. J., et al., "Rate of Total Hip Arthroplasty: A Population Based Study," New England Journal of Medicine, vol. 307, Nov. 11, 1982, pp. 1242-1245.

References

References

1. Aglietti, P., Insall, J., Walker, P., Trent, P., "A New Patellar Prosthesis, It's Design and Application," *Clin. Orthop.*, 107:175, 1975.

2. *American Society for Materials and Testing F-4 Committee on Surgical Implants*, Oct. 1970, American Society for Materials and Testing, Philadelphia, Pa., 1970.

3. Bagwell, J., DePuy Inc., Warsaw, Indiana, Personal communications, March, 1981.

4. Banta, D. H., Brown, S., Behney, C., "Implications of the 1976 Medical Devices Legislation," *Man & Medicine*, 3:131, 1978.

5. Bryan, R. S., Peterson, L. F., "Polycentric Total Knee Arthroplasty," *Clin. Orthop.*, 145:23, 1979.

6. Bryan, R. S., Peterson, L. F., Combs Jr., J. J., "Polycentric Knee Arthroplasty: A Preliminary Report of Post-Operative Complications in 450 Knees," *Clin. Orthop.*, 94:148, 1973.

7. Buckhardt, J., Personal communication, March, 1981.

8. Burnett, B., DePuy Inc., Warsaw, Indiana, Personal communication, March, 1981.

9. Burstein, A. H., Hospital for Special Surgery, N. Y., N. Y., Personal communication, April and May, 1981.

10. Calandruccio, R. A., "Arthroplasty," in *Campbell's Operative Orthopaedics*, ed. by Edmunson, A. J., and Crenshaw, A. H., C. V. Mosby Co., St. Louis, 1980.

11. Cavarocchi, N., American Academy of Orthopaedic Surgeons, Personal communicaton, May, 1981.

12. Chao, E. Y., Wong, H. W., Frain, W. E., Coventry, M. B., "Stress Analysis of the Geometric Knee Under Static Loading," New York, American Society of Mechanical Engineers, 77-Bio-6, 1977.

13. Charnley, J., "Arthroplasty of the Hip: A New Operation," *Lancet*, 1129, 1961.

14. Charnley, J., "Clean-Air in the Operating Room," *Clev. Clinic Q.*, 40:99, 1973.

15. Charnley, J., "The Long Term Results of Low Friction Arthroplasty of the Hip Performed as a Primary Intervention," *J. Bone Joint Surg.*, 54-B(1):61, 1972.

16. Charnley, J., "Post-Operative Infection After Total Hip Replacement with Special Reference to Air Contamination in the Operating Room," *Clin. Orthop.*, 87:167, 1972.

17. Charnley, J., and Eftekhar, N., "Post-Operative Infection in Total Prosthetic Replacement Arthroplasty of the Hip Joint," Br. J. Surg. 56:45, 1969.

18. Childress, D. S., Northwestern University Rehabilitation Engineering Program, Personal communication, May, 1981.

19. Coombs, F., Veterans Administration Rehabilitation Engineering, Research and Development, Personal communication, March, 1981.

20. Coventry, M. B., "Two-Part Total Knee Arthroplasty: Evolution and Present Status, " Clin. Orthop., 145:29, 1979.

21. Coventry, M. B., Upshaw, J. E., Riley, ?. H., Finerman, G. A. Turner, R. A., "Geometric Total Knee Arthoplasty: I. Conception, Design, Indications, Surgical Technique," Clin. Orthop., 94:171, 1973.

22. Dillon, J. G., Bureau of Medical Devices, Executive Secretary Orthopaedic Section, Personal communications, March, April, May, 1981.

23. Dillon, J. G., U. S. Department of Health and Human Services, Food and Drug Administration, Bureau of Medical Devices, Letter to Orthopaedic Manufacturers, May 9, 1978.

24. DuPont, J. A., and Charnley, J., "Low-Friction Arthorplasty of the Hip for the Failure of Previous Operations," J. Bone Joint Surg. 54-B(1):77, 1972.

25. Farner, S., Orthopaedic Equipment Corp., Warsaw, Indiana, Personal communication, March, 1981.

26. Finerman, G. A., Coventry, M. B., Riley, L. H., Turner, R. H., and Upshaw, J. E., "Anametric Total Knee Arthroplasty," Clin. Orthop., 145:85.

27. Frankel, V. H., Orthopaedic Institute N.Y. N. Y., Personal communications, April, 1981.

28. Frankel, V. H., and Nordia, M., Basic Biomechanics of the Skeletal System, Lea and Febiger, Philadelphia, Pa., 1980.

29. Freeman, M. A., Insall, J., Besser, W., Walker, P. S., and Hallel, T., "Excicsion of the Cruciate Ligaments in Total Knee Replacements," Clin. Orthop., 126:209, 1977.

30. Freeman, M. A., Swanson, S. A., Todd, R. C., "Total Replacement of the Knee Using the Freeman-Swanson Knee Prosthesis," Clin. Orthop., 94:153, 1973.

31. Furgeson, J., Biomet Inc., Warsaw, Indiana, Personal communication, March, 1981.

32. Fuson, R., Zimmer-USA, Warsaw, Indiana, Personal communications, March, 1981.

33. Gordon, S., National Institute for Arthritis, Metabolic, and Digestive Diseases, Personal communications, March, 1981.

34. U. S. Department of Health and Human Services, Public Health Service, Report of the Graduate Medical Education National Advisory Committee.

35. Gunston, F. H., "Polycentric Knee Arthroplasty," *Clin. Orthop.*, 94:128, 1973.

36. Gunston, F. H., "Polycentric Knee Arthroplasty," *J. Bone Joint Surg.* 53-B:272, 1971.

37. Gyory, A. N., Chao, E. Y., Stauffer, R. N., "Functional Evaluation of Normal and Pathologic Knees During Gait," *Arch. Phys. Med. Rehab.*, 57:571, 1976.

38. Hagans, J., Veterans Administration, Cooperative Studies Program, Personal communication, April, 1981.

39. Herman, M., Zimmer-USA, Warsaw, Indiana, Personal communication, March, 1981.

40. Herndon, S., Zimmer-USA, Warsaw, Indiana, Personal communication, March, 1981.

41. Hori, R. Y., Lewis, J. L., Zimmerman, J. R., and Compere, C. L., "The Number of Total Joint Replacements in the U.S.," *Clin. Orthop.*, 132:46, 1978.

42. Ingelhart, J. K., "A Different Direction on Devices," *Nat. J.*, May 29, 1976, p. 753.

43. Insall, J. N., Ranawat, C. S., Aglietti, P., Shine, J., "A Comparison of Four Models of Total Knee Replacement Prosthesis," *J. Bone Joint Surg.*, 58-A(6): 754, 1976.

44. Insall, J. N., Ranawat, C. S., Scott, N. W., Walker, P. S., "Total Condyalar Knee Replacement," *Clin. Orthop.*, 120:149, 1976.

45. Insall, J. N., Tria, A. J., Scott, W. N., "The Total Condylar Knee Prosthesis: The First Five Years," *Clin. Orthop.*, 145:68, 1979.

46. Kelsey, J. L., Pastides, H., Bisbee, Jr., G. E. *Musculo-Skeletal Disorders Their Frequency of Occurence and Their Impact on the Population of the United States*, Prodist, N.Y., 1978.

47. Lane, M., Orthopaedic Institute N.Y., N. Y., Personal communication, February, 1981.

48. Lemmon, T., Zimmer-USA, Warsaw, Indiana, Personal communication, March, 1981.

49. Lanning, R., Veterans Administration Director of Surgical Services, Personal communication, March, 1981.

50. Markoff, K., University of California at Los Angeles, Personal communication, April, 1981.

51. Miller, E., University of Cincinatti, Personal communication, March, 1981.

52. Murphy, E. F., Veterans Administration, Office of Technology Transfer, Personal communication, February, 1981.

53. National Academy of Sciences, "Informal Papers of a Workshop on the Control of Operating Room Airborne Bacteria," Nov. 8-10, 1974, under Contracts #V101-(134)P-75 and V101(134)P-350 between the Veterans Administration and the National Academy of Sciences; and Contract #SRS-500-75-0001 and HEW-105-76-4103 between the Dept. of Health, Education and Welfare and the National Academy of Sciences.

54. The National Archive of the U.S. Federal Register, Dept. of Health, Education and Welfare, Food and Drug Administration, Friday, July 28, 1978, Part II, Vol. 43-No. 146.

55. Nickel, V., University of California at San Diego, Personal communication, March, 1981.

56. Noblitt, N., Biomet Inc., Warsaw, Indiana, Personal communication, March, 1981.

57. Northwestern University Rehabilitation Engineering Program, Continmuation Proposal 23-P-55898 submitted to the National Institute of Handicapped Research, December, 1980.

58. O'Handley, D., Jet Propulsion Laboratory, California Institute of Technology, Personal communication, April, 1981.

59. Perry, J., Personal communication, February-May, 1981.

60. Ranawt, C. S., Shine, J. J., "Duo-Condylar Total Knee Arthroplasty," Clin. Orthop., 94:185, 1973.

61. Reid, D. C., Mathewson, M., "Rehabilitation in Total Hip Replacement: A Survey of the Literature and Current Practice," Physiotherapy Canada, 27:185, 1975.

62. Reiss, J., Personal communication, February, 1981.

63. Reswick, J., National Institute of Handicapped Research, Personal communication, March, 1981.

64. Riley, L. H., John Hopkins University, Personal communication, April, 1981.

65. Rylee, R., Dow Corning-Wright, Arlington, Tennessee, Personal communication, April, 1981.

66. Rubner, P., National Association of Blue Cross and Blue Shield, Letter of March 13, 1981.

67. Sauer, R., Bureau of Medical Devices, Assistant Director for Program Operations, Letter of April 15, 1981.

68. Shaw, J. A., Murray, D. G., "Knee Joint Simulator," Clin. Orthop., 94:15, 1973.

69. Skolnick, M. D., Coventry, M. B., Ilstrup, D. M., "Geometric Total Knee Arthroplasty," J. Bone Joint Surg. 58-A(6):749, 1976.

70. Stauffer, R. N., Mayo Clinic, Personal communication, February-April, 1981.

71. Traub, J., National Institute of Handicapped Research, Personal communication, March, 1981.

72. U.S. Department of Commerce, National Bureau of Standards, "Retrieval and Analysis of Orthopaedic Implants," NBS special publication #472, April, 1977.

73. U.S. Department of Health and Human Services, Food and Drug Administration, Bureau of Medical Devices, "Guideline for the Arrangement and Content of a Premarket Approval Application (PMA)," issued November, 1980.

74. U.S. Department of Health and Human Services, Food and Drug Administration, Bureau of Medical Devices, Orthopaedic Section Panel Meeting, March 26, 1981, Washington, D.C.

75. U.S. Department of Health and Human Services, Food and Drug Administration, Freedom of Information Branch, Personal communication, March, 1981.

76. Vargo, D., National Aeronautics and Space Administration, Office of Technology Transfer, Personal communication, March, 1981.

77. Walker, P. S., Human Joints and Their Artificial Replacement, Charles C. Thomas, Illinois, 1977.

78. Walker, P. S., Personal communication, February-May, 1981.

79. Walker, P. S., Hajeh, J. V., "The Load Bearing Area in the Knee Joint," J. Biomech. 5:581, 1972.

80. Walker, P. S., Shoji, H., "Development of a Stabilizing Knee Prosthesis Employing Physiologic Principles," Clin. Orthop., 94:222, 1973.

81. Walker, P. S., Shoji, H., Erkman, M. J., "The Rotational Axis of the Knee and Its Significance to Prosthesis Design," Clin. Orthop., 89:160, 1972.

82. Wendt, T., Zimmer-USA, Warsaw, Indiana, Personal communication, February, 1981.

83. Weinstein, A., Tulane University, Personal communication, February-March, 1981.

84. Weissman, S., Howmedica Inc., Personal communication, February, 1981.

85. Wilson Jr., P. D., Hospital for Special Surgery, N.Y., N.Y., Personal communication, February-March, 1981.